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EFFECT OF ADDITIONS OF AROMATICS ON THE KNOCKING CHARACTERISTICS OF SEVERAL 100-OCTANE FUELS AT TWO ENGINE SPEEDS

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SUMMARY

Tests at two engine speeds were conducted on six representative fuels rated at 100-octane number by the C.F.R. aviation method. Blends of these fuels with benzene, toluene, xylene, and isopropyl ether comprise nine other fuels, making a total of 15 fuels tested in the present program.

The data indicate that aromatic additions in small quantities cause substantial increases in rich-mixture performance with little or no detrimental effect at the leaner mixtures. Large proportions of aromatics result in large increases in rich-mixture performance but tend to lower performance at leaner mixtures and may cause afterfiring. No preignition was evident in any of the tests.

Introduction of engine speed as a variable complicates the problem of knock rating considerably. Different engine speeds gave different knock ratings. There was some correlation between speed and knock rating for a given inlet-air temperature, but this was only a general trend.

The variation in percent paraffins, naphthenes, and olefins was too small in these fuels to permit any evaluation of base stocks or blending agents on the basis of composition.

INTRODUCTION

The tests on eight representative 100-octane fuels (C.F.R. aviation method, reference 1), reported in reference 2, have been extended to include four more fuels of 100-octane number by the same method, along with further tests on fuels 7 and 8 of reference 2. The earlier tests were all made at 2000 rpm; whereas the present results are reported for both 2000 and 3100 rpm. The effect of the addition of aromatics to these fuels and the effect of engine speed have both been determined. These tests have been carried out upon the recommendation of the NACA Subcommittee on Aircraft Fuels and Lubricants. The results are presented in this report. The tests were made at the Langley Memorial Aeronautical Laboratory of the National Advisory Committee for Aeronautics during 1941 and 1942.

FUELS TESTED

NACA fuels 7 and 8, reported in reference 2, were tested at a higher engine speed to supplement the data already obtained on them. Fuel 7 was also tested with an addition of 15 percent benzene by volume containing 3.0 ml of tetraethyl lead per gallon.

Four additional fuels, test results of which are presented in this report, will be designated NACA fuels 9, 10, 11, and 12, continuing the numbering system begun in reference 2.

The compositions of fuels 7 through 12 as to base stocks and blending agents are listed in table I, along with the tetraethyl lead content and the octane number by the C.F.R. aviation method. An approximate hydrocarbon analysis of these fuels is given in table II. The complete inspection data are given in table III for the four new fuels, and figure 1 shows the distillation curves for these four fuels. Three of these gasolines contain large percentages of alkylate. The other is a blend of a natural gasoline blending naphtha in a commercial iso-octane of about 91-octane number. Fuel 12 is the only one containing appreciable quantities of aromatics, the main constituents in all being paraffins. The tetraethyl lead content is approximately the same for the four fuels, and the octane numbers are all very close to 100.

To each of these four fuels was added 15 percent benzene containing 3.0 ml tetraethyl lead per gallon, for tests to determine the effects of aromatic additions. Fuel 11 was also tested separately with 15-percent additions of toluene, xylene, and isopropyl ether, and a 40-percent addition of mixed aromatics, all containing 3.0 ml tetraethyl lead per gallon. The percentages in all cases are by volume, on the assumption of exact additivity of the blending components. The mixed aromatics consisted of 50 percent toluene, 37.5 percent xylene, and 12.5 percent benzene. The hydrogen-carbon ratios and the heats of combustion of the four fuels and the various fuel blends are given in table IV. In the tables and figures tetraethyl lead is designated TEL, and values given are in milliliters per gallon.

APPARATUS

A description of the Lycoming O-1230 single-cylinder set-up used in these tests is presented in reference 2. The cylinder differed from the one used in reference 2 only in the spark plugs. Alterations were made to provide for long-reach spark plugs instead of the short-reach bottom-seating plugs previously used. The long-reach plugs were installed so that the electrodes were approximately flush with the inner surface of the combustion chamber. This change eliminated the small pockets at the spark plugs and provided better lean-mixture operation. The difference in the combustion path caused by this change is shown in figure 2. The optimum spark advance was decreased by about 8° at 2000 rpm. Bendix 5-OLS, Bendix 5S-6, and Champion C-34S spark plugs were used for these tests.

A "Stancal" magnetostriction pickup and an oscillograph were used for determining the point at which knock was encountered. The first derivative of the rate of change of pressure was used for this determination.

The following engine conditions were maintained constant:

	Engine speed 2000 rpm	Engine speed 3100 rpm
Spark advance, °B.T.C.	21	29
Coolant inlet temperature, °F	250	250
Compression ratio	7.0	7.0
Oil outlet temperature, °F	165	175

TEST PROCEDURE

The general test procedure used was the same as that described in reference 2. The "Stancal" pickup was used in place of the "audible knock" method previously used to establish maximum permissible performance level because the noise level near the engine at the higher speed (3100 rpm) made the knock difficult to hear. The point at which knock could first be detected on the oscillograph was used as the condition at which data were taken. Tests showed that this level of knock corresponded very closely with the knock level obtained at 93-percent audible knock inlet pressure at 2000 rpm, which was used for all the tests reported in reference 2. All values of inlet pressure are in inches of mercury absolute.

The spark advance used for the tests of this report differed from that used previously in that the spark was retarded for one-half of 1 percent drop in power instead of the 1 percent used in reference 2. It is thought that this comes nearer to actual service conditions, and the efficiency is slightly higher. The optimum spark advance was also affected by the change to long-reach spark plugs as mentioned before.

During the course of these tests the engine was thoroughly inspected after every 20 hours of operation. A standard routine was adopted which included checks on tappet clearances and valve timing, spark synchronization and timing, injection timing, spark-plug condition, combustion-chamber condition (carbon), friction, and a rough check on oil consumption. Other less important checks were also made.

Tests were made each morning with S-1 (or S-1A) fuel for checking maximum permissible inlet pressure and power. At the conclusion of tests in the afternoon check runs were made with S-1 (or S-1A) + 1.0 ml tetraethyl

lead. If the maximum permissible inlet pressure did not check within ±1.0 inch of mercury at a fuel-air ratio of 0.07 or, if the power did not check within 5 pounds per square inch brake mean effective pressure at a fuel-air ratio of about 0.085 and at a given inlet pressure, the engine was examined to determine the cause.

Aside from the differences just mentioned, the test procedure was the same as described in reference 2.

TEST RESULTS

At present the commonly accepted method of rating fuels is to compare their knock-limit performance with that of mixtures of iso-octane (2,2,4 trimethylpentane) and normal heptane for fuels below 100-octane number, or with that of iso-octane plus various quantities of tetraethyl lead for fuels of better performance than 100-octane-number fuels. Suitable calibrated reference fuels are used in actual engine operation because of their greater availability. Since the fuels tested were expected to be equal to or better than 100 octane in the Lycoming cylinder; the engine was calibrated only with the reference fuels S-1 and S-1 plus tetraethyl lead. Because S-1 became unavailable during the course of these tests, S-1A was used in its place for some of the reference curves. Although exhaustive tests were not run, those that were run showed S-1 and S-1A to have the same knock limits within the experimental error.

Tests at 2000 rpm and 250° F Inlet-Air Temperature

Performance of reference fuels.- The reference fuels for the tests at 2000 rpm and 250° F inlet-air temperature were S-1A and S-1A plus various quantities of tetraethyl lead. Figure 3 shows the performances obtained for the reference fuels, expressed as a function of the fuel-air ratio. The maximum knock mixture comes at a fuel-air ratio of about 0.07. At leaner mixtures there was a marked increase in the maximum permissible indicated mean effective pressure. This increase is in contradiction to the behavior reported in reference 2 for this cylinder. The difference is attributed to the elimination of the pockets at the spark plugs by the change to long-reach plugs. The indicated fuel consumption was found to be slightly lower at the extremely lean mixtures owing to the better lean-

mixture operation. For the richer mixtures, however, the indicated fuel consumption was the same as before within the experimental error.

Performance of NACA fuels 9, 10, 11, and 12.- Figure 4 shows the performance of NACA fuels 9, 10, 11, and 12. The S-1A reference curves are superimposed on the maximum permissible indicated mean-effective-pressure curves so the fuels can be compared on a quantitative basis and given a knock rating. Fuel 11 is appreciably better than the other three throughout most of the fuel-air-ratio range. All four fuels have their best rating relative to S-1A at fuel-air ratios of 0.08 to 0.09. In this range they are all better than S-1A + 1.0, and fuel 11 is slightly above S-1A + 2.0. It is interesting to note that many of these and the following fuels have perfomance curves that rise very steeply at the extremely rich mixtures. However, in most cases these steep rises come at mixtures too rich to be of any practical value.

The indicated fuel consumption is about the same for all four fuels throughout the fuel-air-ratio range. Most ordinary fuels containing little or no aromatics have this characteristic. This result agrees with reference 2. The reference fuels for these engine conditions show the same indicated fuel consumptions as the test fuels. The point of minimum fuel consumption is at a fuel-air ratio of about 0.06, slightly lower than the chemically correct fuel-air ratio.

In figure 5 are plotted the results of tests of fuels 9, 10, and 11 conducted by the Esso Laboratories, who furnished the data and granted permission to publish. These tests were made according to the C.F.R. supercharge method (reference 3). Fuel 11 here rates slightly higher than the others, with 9 and 10 following in that order. The fuels thus rate in the same order as in the Lycoming cylinder at 2000 rpm and 250° F inlet-air temperature although the quantitative ratings do not agree. The rich-mixture rating for the C.F.R. supercharge method is probably at a fuel-air ratio of about 0.10. At this point the ratings on the C.F.R. engine vary from S-1 + 0.2 for fuel 10 to S-1 + 0.6 for fuel 11. These ratings are in general lower than corresponding ratings on the Lycoming cylinder, those on the Lycoming cylinder varying from about S-1A + 0.7 to S-1A + 1.6. The values of indicated mean effective pressure are much higher for the Lycoming cylinder than for the C.F.R. cylinder, for both the reference and the test fuels.

Effect of additions of aromatics and isopropyl ether.- Figures 6, 7, 8, and 9 show the effect of the addition of 15 percent benzene to fuels 9, 10, 11, and 12, respectively. The general result was about the same for all the fuels. The addition of benzene increased the performance slightly at the leaner mixtures and considerably at mixtures richer than about 0.09. The main difference among the fuels was the amount of the rich-mixture improvement. This improvement in permissible indicated mean effective pressure varied from 8 to 13 percent and from 0.6 to 0.9 ml tetraethyl lead based on S-1A at a fuel-air ratio of 0.10. Fuel 12 showed the greatest improvement at extremely rich mixtures. Since this fuel originally contained some aromatics, the possibility is suggested that the rate of rich-mixture improvement caused by the addition of aromatics increases as the percentage of aromatics increases. This statement has been found true in some other cases.

The indicated fuel consumption was not changed by the addition of the benzene except at the extremely rich mixtures. The change here was small and occurred at mixtures too rich to be of any practical value.

Table V lists data obtained by Esso Laboratories on NACA fuels 9, 10, 11, and 12, each with 15 percent benzene, and fuel 11 with 15 percent isopropyl ether. By a comparison of these values with the values in figure 5, it is seen that the rich-mixture ratings were increased markedly by the addition of the benzene, the amount of the increase varying from about 0.6 to about 2.1 ml tetraethyl lead based on S-1. The improvement to fuel 11 was by far the greatest of the improvements to the three fuels in the C.F.R. cylinder; whereas it was the least of the improvements to these three fuels in the Lycoming cylinder.

The effects of additions of toluene, xylene, and isopropyl ether to fuel 11 are shown in figures 10, 11, and 12. The performance at rich mixtures was improved by each of these additions in the same manner as by the benzene additions. The toluene blend gave a rich-mixture performance very slightly higher than the benzene blend with fuel 11, and the performance of the xylene blend was lower than either. The isopropyl ether blend gave about the same rich-mixture improvement as the xylene blend. The performance in the vicinity of the maximum knock mixture was decreased slightly for all the aromatic blends with fuel 11; whereas the isopropyl ether blend gave

slightly improved performance throughout the fuel-air-ratio range. The indicated fuel consumptions for these blends showed little or no difference from those for straight fuels throughout the practical operating range.

Esso Laboratories obtained a much greater increase in rich-mixture performance for the isopropyl ether blend with fuel 11 than was obtained in the Lycoming cylinder. The C.F.R. supercharge method rich-mixture rating was increased from about S-1 + 0.6 to S-1 + 2.6 by the addition of 15 percent isopropyl ether (table V) while the corresponding increase in the Lycoming cylinder was from S-1A + 1.6 to S-1A + 2.0. The C.F.R. supercharge method tests gave the isopropyl ether blend a higher lean-mixture rating than the benzene blend, which agrees with the results obtained with the Lycoming cylinder.

Figure 13 contains the performance curves of a blend of 40 percent mixed aromatics (50 percent toluene, 37.5 percent xylene, 12.5 percent benzene) with fuel 11. Although the lean-mixture performance was appreciably lower than for the straight fuel, the rich-mixture performance was increased very greatly. The maximum value of indicated mean effective pressure was at approximately 0.12 fuel-air ratio, and here the rating was increased from S-1A + 1.0 to an estimated value of S-1A + 3.9. Some afterfiring, as indicated by the points marked "A" on the indicated mean-effective-pressure curve, was experienced in testing this blend, but it was not serious enough to cause any difficulty. It is thought that the afterfiring originated at the spark plug and therefore did not affect the knock rating. In the absence of preignition a fuel of this type would be very advantageous for take-off or for emergency power.

The indicated fuel consumption for this blend was lower than that for the straight fuel for all mixtures except the very leanest. This decrease amounts to about 6 to 7 percent for a given fuel-air ratio in the cruising-mixture range.

A summary of the effects of the various aromatic additives is shown in figure 14. At these operating conditions the individual aromatics are rated in the following descending order: toluene, benzene, xylene.

Tests at 3100 rpm and 250° F Inlet-Air Temperature

Performance of reference fuels.- S-1 and S-1 plus tetraethyl lead were used as reference fuels for the tests at 3100 rpm and 250° F inlet-air temperature. Figure 15 shows the performance curves for these fuels. It is interesting to note that the values of indicated mean effective pressure for rich mixtures are above the values at the lower speed (fig. 3), but that they are considerably below the values at the lower speed for the leaner mixtures. The maximum knock mixture and the point of minimum indicated fuel consumption are at slightly leaner mixtures than for the lower speed runs. The indicated fuel consumption is slightly higher than for the runs at 2000 rpm for mixtures richer than the maximum knock mixture.

Performance of NACA fuels 7, 7 plus benzene, and 8.- Tests of fuels 7 and 8 at 2000 rpm at inlet-air temperatures of 150° and 250° F were reported in reference 2. At this lower speed there was a marked difference in the performance of the two fuels, fuel 8 giving much better performance than fuel 7. Since the tests reported in reference 2, these fuels have been tested at 3100 rpm. The results of these tests, along with tests of fuel 7 with 15 percent benzene, are presented in figure 16. It is seen that the performance of the three fuels is practically the same except at the extremely rich mixtures. At mixtures richer than 0.11, fuel 7 plus benzene requires about 0.4 ml more tetraethyl lead in S-1 for performance matching than does the straight fuel. The performance of fuel 8 continued to increase with no indication of leveling off at a fuel-air ratio of 0.116, which was the highest value attained. Inasmuch as fuel 8 contains about 15 percent aromatics, it might be expected to have good rich-mixture performance. The addition of 15 percent benzene to fuel 7, however, did not place it on a par with fuel 8 for rich-mixture performance. The only other differences between fuels 7 and 8 are the proportions of phosphoric acid iso-octane and light naphtha. The compositions of these fuels are shown in tables I and II.

Performance of NACA fuels 9, 10, 11, and 12.- In figure 17 are shown the performance curves of fuels 9, 10, 11, and 12. The performance of fuel 12 is considerably lower than that for the other three fuels at the leaner mixtures, having an estimated octane number of 97 at the

maximum knock mixture. The other three fuels have performance curves very near each other except at the richer mixtures. Fuel 11 gives a very slightly better performance than the others throughout most of the fuel-air-ratio range. The fact that fuel 12 has a lower lean-mixture rating and shows more improvement than the other three fuels as the mixture is enriched might be explained by its aromatics content.

Effect of additions of aromatics and isopropyl ether.- In figures 18, 19, 20, and 21 are shown the effects of 15-percent additions of benzene to fuels 9, 10, 11, and 12. The general effect is the same for the four fuels. All showed appreciable improvement at fuel-air ratios greater than 0.11 but showed no improvement in the normal operating range. Performance at extremely lean mixtures was also improved noticeably. Fuel 10 showed the greatest rich-mixture improvement, with 11, 12, and 9 following in that order. The increase for fuel 10 was from S-1 + 0.5 to S-1 + 1.0 at a fuel-air ratio of 0.12. These increases are somewhat smaller than those obtained at 2000 rpm and 250° F inlet-air temperature.

The effects of toluene, xylene, and isopropyl ether additions to fuel 11 are shown in figures 22, 23, and 24. The toluene blend provided a large improvement for fuel-air ratios above 0.10, while the xylene blend showed no appreciable improvement at any mixture. The isopropyl ether blend showed only slight improvement at rich mixtures and at extremely lean mixtures. The improvement for the toluene blend was from S-1 + 1.0 to an estimated value of S-1 + 2.0 at a fuel-air ratio of 0.12. This improvement was of the same order as that obtained at 2000 rpm. Improvements obtained by additions of benzene; xylene, and isopropyl ether were lower than at 2000 rpm. On the basis of the tests at 3100 rpm, the aromatics might be listed according to the improvement derived from small additions to fuel 11 in the following descending order: toluene, benzene, xylene. This is the same order obtained at 2000 rpm.

Indicated fuel consumptions at normal operating mixtures were not changed appreciably by the addition of small amounts of aromatics or isopropyl ether to fuel 11.

In figure 25 are shown the performance curves for a blend of fuel 11 with 40 percent mixed aromatics (50 percent toluene, 37.5 percent xylene, 12.5 percent benzene).

There is a tremendous increase in performance for mixtures richer than 0.105 fuel-air ratio. At 0.12 fuel-air ratio, an increase of 38 percent in the maximum permissible indicated mean effective pressure was recorded. At this mixture an estimated rating of S-1 + 4.0 had been reached. Mixtures richer than 0.12 were not tested, but there is some indication that the performance was beginning to level off. This rating of S-1 + 4.0 is about the same as that obtained at 2000 rpm, the rating at the lower speed being an estimated S-1 + 3.9 at the same fuel-air ratio.

Considerable afterfiring, as indicated by the points marked A on the indicated mean-effective-pressure curve, was encountered at the higher outputs with this fuel. It is not known with certainty that this afterfiring was caused by the spark plugs. The spark plugs were changed from Champion C-34S to Bendix 5S-6 before the richest run, but the change did not diminish the afterfiring. Both of these plugs are cold plugs, however, and it is not known which, if either, is the better for maintaining lower electrode temperatures. At any rate, all the points on the curve represent knocking conditions and, if the afterfiring originated at the spark plugs, the points indicated are true knock points. No evidence of preignition was found.

The performance of the mixed aromatics blend was definitely inferior to that of the straight fuel at cruising mixtures, the knock rating for the aromatic blend being S-1 against a rating of S-1 + 1.1 for the straight fuel at 0.08 fuel-air ratio. Indicated fuel consumptions for the mixed aromatics blend were slightly lower than for the straight fuel for mixtures richer than 0.07, but the difference was probably of little importance. Figure 26 presents a summary of the results obtained from the blends of aromatics with fuel 11 at 3100 rpm.

In most cases at 3100 rpm the fuel-air ratio for maximum indicated mean effective pressure was in excess of 0.12 for the aromatic blends. The Esso data in table V show similar results.

Tests at 2000 rpm and 150° F Inlet-Air Temperature

<u>Performance of reference fuels</u>.- When tested at 2000 rpm and 150° F inlet-air temperature, the reference fuels, S-1A and S-1A plus tetraethyl lead, gave the performances

shown in figure 27. The levels of performance shown by the indicated mean-effective-pressure curves are somewhat higher than the levels for the same fuels at the higher inlet-air temperature. The curves have the same general shape as those for the 250° F inlet-air temperature, the main difference being the amount of rich-mixture appreciation. The higher inlet-air temperature caused a greater increase in performance as the mixture was enriched.

The indicated fuel consumptions for the four reference fuels can be represented by a single line, and this line is nearly identical with the one obtained at the higher inlet-air temperature.

Performance of fuel 11 with and without benzene addition.- Figure 28 shows the performance of fuel 11 and fuel 11 plus 15 percent benzene. There is little difference in the shape of the two curves. Both curves are peculiar in that they rise almost vertically at mixtures richer than 0.14. Unfortunately, this rise occurs at mixtures too rich to be of practical value. The benzene blend is slightly better than the straight fuel at rich and at extremely lean mixtures. The indicated fuel consumptions for the two fuels are the same for normal operating mixtures.

Tests at 3100 rpm and 150° F Inlet-Air Temperature

Performance of reference fuels.- The performance curves for the reference fuels for tests at 3100 rpm and 150° F inlet-air temperature are shown in figure 29. It will be noted that their shape is somewhat similar to the shape of the reference curves for the same inlet-air temperature and 2000 rpm, shown in figure 27. The slope on the rich side is slightly greater than for the runs at 2000 rpm. The difference seems to be characteristic of the reference curves at the two speeds. Maximum knock mixture is at about 0.07 fuel-air ratio for all of the reference curves except those at 3100 rpm and 250° F inlet-air temperature (fig. 15). For these test conditions the maximum knock mixture is somewhat leaner.

Performance of fuel 11 with and without benzene additions.- At 3100 rpm and 150° F inlet-air temperature the benzene blend was better than the straight fuel throughout the entire fuel-air-ratio range. The performance curves, presented in figure 30, show that the

greatest difference is at the richer mixtures, as has been the case for practically all of the aromatic blends at all operating conditions. At a fuel-air ratio of 0.10 the improvement is from S-1A + 1.2 to S-1A + 2.3.

The indicated-fuel-consumption curve for the benzene blend is typical of those for aromatic blends. There is little or no difference between the fuel consumptions for the straight fuel and the benzene blend at normal operating mixtures, but the benzene blend shows slightly lower consumption at extremely rich mixtures.

Effect of Speed on Knock Rating

The general effect of engine speed on the performance is the same for fuels 7 through 12. Figures 31(a), (b), (c), (d), (e), and (f) show this effect for these fuels. In nearly every case the lower speed performance is considerably better for all of the leaner mixtures up to a fuel-air ratio of about 0.10.

It is interesting to note that the actual knock rating expressed in terms of the reference fuels was generally higher for the lower speed runs at the higher inlet-air temperature. A study of table VI shows that in most cases the knock rating was higher at the lower speeds, except at the rich mixtures, where there was a tendency for the runs at both speeds to approach equal ratings. This trend, however, did not hold true for the lower inlet-air temperature. For these runs the higher speeds gave the higher knock ratings.

Effect of Inlet-Air Temperature on Knock Rating

Figure 32(a) shows the performance curves for fuel 11 at two inlet-air temperatures, 250° and 150° F, for an engine speed of 2000 rpm. Figure 32(b) shows the same curves for 3100 rpm. In general a higher level of performance was obtained at the lower temperature. The indicated mean-effective-pressure curves for the runs at 2000 rpm are somewhat similar, the main differences being the locations of the maximum and minimum points. Except for the points at the maximum knock mixture, the maximum and minimum points occur at a slightly higher fuel-air ratio for the higher temperature. This same effect was noted in reference 2 to a somewhat greater extent. The

curve for 150° F inlet-air temperature rises very steeply after passing through its minimum point at about 0.13 fuel-air ratio. The curve for 250° F might have been of the same form had the mixture been enriched sufficiently past the minimum point at 0.14 fuel-air ratio. It was stated in reference 2 that differences in the amount of vaporization at the two temperatures might be influencing the reaction. No other explanation is evident at the present time.

The effect just mentioned occurs to a very marked degree at the higher engine speed. Figure 32(b) shows that the curve for 250° F inlet-air temperature did not reach its maximum point until a fuel-air ratio of 0.12 was reached. The corresponding maximum point for the 150° F curve occurs at about 0.085 fuel-air ratio.

The indicated-fuel-consumption curves for the 2000 rpm runs show a lower consumption throughout nearly the entire fuel-air-ratio range for the 150° F runs. A comparison of figures 28 and 8 shows that this same difference occurs with the benzene blends with fuel 11 at the two inlet-air temperatures. The reason is not obvious. It does not occur at the higher engine speed.

Effect of Spark Advance on Knock Rating

In order to determine some of the effects of spark advance on the knock rating of a fuel, a series of runs was made at 3100 rpm with the spark setting normally used for runs at 2000 rpm. The results of these tests are shown in figure 33. It is noted that the performance with the retarded spark was considerably better in the vicinity of the maximum knock mixture but that the difference became smaller as the mixture was leaned or enriched from this point. Between fuel-air ratios of 0.10 and 0.13 the maximum permissible indicated mean effective pressure became less for the retarded spark, although the permissible inlet pressure remained slightly higher. This trend is reflected very slightly in the indicated fuel consumption. At mixtures richer than 0.13 the permissible inlet pressure increased very rapidly with very little increase in indicated mean effective pressure.

The indicated fuel consumption for the lean and extremely rich mixtures was slightly higher for the retarded spark. The difference at mixtures between 0.08 and 0.11

was so small that it did not show up in the curves. In many cases it might be desirable to obtain the increased performance at the expense of the very slight increase in fuel consumption. It is interesting to note that at mixtures between 0.07 and 0.10, the spark may be retarded and the same power maintained at a leaner mixture. Therefore, while operating at the knock limit, one may retard the spark and maintain the same power at a lower fuel consumption.

It is not known to what extent retarded spark might affect other fuels but, because the optimum spark setting is substantially the same for most fuels, it is probable that the same possibilities of increased performance or lower fuel consumption for a given performance might be expected for most fuels under these same conditions of engine operation.

SUMMARY OF KNOCK RATINGS

Table VI presents the values of maximum permissible indicated mean effective pressure expressed as a percentage of the values for S-1 (or S-1A) for the reference fuels. Table VII contains the same data for the test fuels. In general there seems to be considerable variation among these percentages for any one test fuel at different fuel-air ratios. This variation in especially great in the case of the fuel containing 40 percent aromatics. There is also considerable difference between the percentages at 2000 and 3100 rpm and between the percentages at 150° and 250° F inlet-air temperature.

In table VIII are shown the values of maximum permissible mean effective pressure for the fuel blends expressed as a percentage of the values for the straight fuels. This table gives a direct picture of the effects of the various additives at all engine conditions used.

The individual knock ratings of the fuels at each engine condition based on the reference fuels for that condition are presented in table IX. The variations here are similar to those in tables VI and VII. It is apparent that any method of averaging these values would give only misleading results.

CONCLUSIONS

The data of this report indicate that:

1. The addition of aromatics permits an appreciable increase in the rich-mixture performance of this series of fuels in practically all cases. In some cases slight improvement is obtained in the extremely lean-mixture performance. Large proportions of aromatics tend to decrease the performance at intermediate mixtures.

2. The increase in rich-mixture performance caused by small additions of aromatics is in general less for the higher speed.

3. The addition of large amounts of aromatics causes large increases in rich-mixture performance but also may cause afterfiring. Preignition was not detected in any case.

4. The addition of small quantities of aromatics results in little or no change in indicated fuel consumption at normal operating mixtures. Large proportions of aromatics result in slightly lower indicated fuel consumption throughout most of the fuel-air-ratio range, only the leanest mixtures showing no change.

5. The addition of small amounts of isopropyl ether has about the same effect as the addition of aromatics, except that the rich-mixture improvement is slightly less than that for the addition of benzene or toluene.

6. The aromatics and isopropyl ether might be classified in the following descending order according to the benefits derived from additions of small quantities to fuel 11: toluene, benzene, isopropyl ether, xylene.

7. The performance can be increased considerably in the vicinity of the maximum knock mixture by retarding the spark a moderate amount. The increase in fuel consumption is very small. When operating at the knock limit it is possible to retard the spark and maintain the same power at a leaner mixture and thus at a lower fuel consumption.

8. The variation in percent paraffins, naphthenes, and olefins was too small in these fuels to permit any evaluation of base stocks or blending agents on the basis of composition.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va.

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TABLE I.- COMPOSITION OF FUELS TESTED

NACA fuel	Amount of TEL per gallon (ml)	Composition of fuel	Octane number by C.F.R. aviation method
7	2.74	60 percent phosphoric acid iso-octane in 40 percent light naphtha	100.0
8	2.79	70 percent phosphoric acid iso-octane in 15 percent light naphtha and 15 percent benzene	100.0
9	2.91	56 percent aviation alkylate and 9 percent hydropentanes in 74-octane number straight run	97.9
10	2.78	46 percent natural gasoline blending naphtha in commercial iso-octane of about 91-octane number	S-1 + 0.01
11	3.00	50 percent alkylate in Midway-type base stock	S-1 + 0.01
12	3	42 percent alkylate in Houdry-type base stock	100.0

TABLE II.- HYDROCARBON ANALYSIS OF FUELS TESTED

NACA fuel	Paraffins (percent)	Naphthenes (percent)	Olefins (percent)	Aromatics (percent)
7	93	4	2	1
8	81	2	2	15
9	81	17	0	2
10	93	7	0	0
11	85	14	0	1
12	74	13	4	9

TABLE III

INSPECTION DATA ON NACA FUELS 9, 10, 11, AND 12

NACA fuel	9	10	11	12
Fuel type	Straight run 74 + alkylate + hydropentanes	Commercial isooctane + blending naphtha	Midway base + alkylate	Houdry base + alkylate
Composition, percentage blending agent in base stock	50 percent alkylate 9 percent hydropentanes	46	50	42
Gravity, deg. A.P.I.	69.6	71.5	68.2	66.5
Reid vapor pressure, lb/sq in.	6.7	7.00	6.5	6.2
Amount of TEL per gallon, ml	2.91	2.78	3.00	3
Initial boiling point, °F	109	104	108	106
10 percent evaporation	147	136	151	150
20 percent evaporation	162	147	167	167
50 percent evaporation	207	190	206	210
90 percent evaporation	247	260	242	252
Final boiling point, °F	288	345	324	308
Percentage recovery	98	98	98	98
Percentage loss	1.5	1.0	------	1.2
Percentage residue	0.5	1.0	------	0.8
Accelerated aging gum, mg/100 ml	------	2.0	------	3.0
Copper dish gum, mg/100 ml	2.0	3.2	1	3
Copper dish corrosion	Pass	------	------	Pass
Octane number by C.F.R. aviation method	97.9	S-1 + 0.01	S-1 + 0.01	100.0
Approximate composition:				
Percentage paraffins	81	93	85	74
Percentage naphthenes	17	7	14	13
Percentage olefins	0	0	0	4
Percentage aromatics	2	0	1	9

TABLE IV

HYDROGEN-CARBON RATIOS AND HEATS OF COMBUSTION OF NACA FUELS 9 TO 12 AND FUEL MIXTURES

Fuel	Specific gravity	Hydrogen (percent)	Carbon (percent)	H/C	Fuel-air ratio for complete combustion	Gross heat of combustion (Btu/lb)	Net heat of combustion (Btu/lb)
9	0.6937	15.47	84.53	0.183	0.0663	20,520	19,057
10	.6881	15.68	84.32	.186	.0661	20,390	18,907
11	.7017	15.75	84.25	.187	.0660	20,460	18,970
12	.7063	14.97	85.03	.176	.0668	20,320	18,904
85 percent 9 15 percent benzene	.7208	14.06	85.94	.164	.0678	20,057	18,727
85 percent 10 15 percent benzene	.7163	14.23	85.77	.166	.0676	19,949	18,603
85 percent 11 15 percent benzene	.7275	14.30	85.70	.167	.0675	20,013	18,660
85 percent 12 15 percent benzene	.7316	13.67	86.33	.158	.0682	19,901	18,608
85 percent 11 15 percent toluene	.7253	14.51	85.49	.170	.0673	20,078	18,706
85 percent 11 15 percent xylene	.7243	14.64	85.36	.172	.0672	20,143	18,758
85 percent 11 15 percent isopropyl ether	.7046	15.46	82.13	.188	.0659	19,918	18,456
60 percent 11 40 percent mixed aromatics	.7652	12.67	87.33	.145	.0693	19,535	18,362

TABLE V

RATINGS OF NACA FUELS 9, 10, 11, AND 12 WITH BENZENE ADDITIONS AND FUEL 11 WITH ISOPROPYL ETHER ADDITION BY C.F.R. SUPERCHARGE METHOD

[Data from Esso Laboratories]

Fuel	C.F.R. supercharge method ratings			
	Lean mixture	Rich mixture	Maximum imep (lb/sq in.)	Fuel-air ratio for maximum imep
85 percent 9 + 15 percent leaded benzene	S-1 + 0.3	S-1 + 1.2	185	0.133
85 percent 10 + 15 percent leaded benzene	95 octane	S-1 + 0.8	176	.123
85 percent 11 + 15 percent leaded benzene	98 octane	S-1 + 2.7	196	.129
85 percent 12 + 15 percent leaded benzene	98 octane	S-1 + 2.6	195	.132
85 percent 11 + 15 percent leaded isopropyl ether	S-1 + 0.1	S-1 + 2.6	195	.133

TABLE VI

RELATIONSHIP BETWEEN FUEL-AIR RATIO AND MAXIMUM PERMISSIBLE INDICATED MEAN EFFECTIVE PRESSURE EXPRESSED AS A PERCENTAGE OF S-1 (OR S-1A)

[Temperatures shown refer to inlet-air temperatures]

Fuel-air ratio	Maximum permissible imep, percent S-1 (S-1A)											
	S-1 + 0.5	S-1 + 1.0				S-1 + 2.0			S-1 + 3.0			
	3100 rpm 250° F	2000 rpm 250°F	3100 rpm 250°F	2000 rpm 150°F	3100 rpm 150°F	2000 rpm 250°F	2000 rpm 150°F	3100 rpm 150°F	2000 rpm 250°F	3100 rpm 250°F	2000 rpm 150°F	3100 rpm 150°F
0.05	113	124	133	107	124	140	130	134	149	158	---	137
.06	111	125	121	112	121	139	129	133	152	159	154	139
.07	115	125	122	117	119	140	135	129	155	160	158	140
.08	115	122	123	118	117	139	138	128	161	160	154	142
.09	114	117	123	120	117	134	140	128	155	154	152	141
.10	112	119	118	120	116	133	139	129	150	146	151	139
.11	109	117	116	119	117	132	139	131	147	147	150	139
.12	107	115	120	119	118	131	138	132	146	---	151	141
.13	---	116	---	116	114	132	135	125	146	---	150	---
.14	---	116	---	112	---	132	130	---	151	---	145	---

TABLE VII

RELATIONSHIP BETWEEN FUEL-AIR RATIO AND MAXIMUM PERMISSIBLE INDICATED MEAN EFFECTIVE PRESSURE, EXPRESSED AS A PERCENTAGE OF S-1 (OR S-1A)

[Temperatures shown refer to inlet-air temperatures]

Fuel-air ratio	Maximum permissible imep, percent of S-1 (or S-1A)														
	Fuel 7	85 percent fuel 7, 15 percent benzene	Fuel 8	Fuel 9		85 percent fuel 9, 15 percent benzene		Fuel 10		85 percent fuel 10, 15 percent benzene		Fuel 12		85 percent fuel 12, 15 percent benzene	
	3100 rpm 250°F	3100 rpm 250°F	3100 rpm 250°F	2000 rpm 250°F	3100 rpm 250°F	2000 rpm 250°F	3100 rpm 250°F	2000 rpm 250°F	3100 rpm 250°F	2000 rpm 250°F	3100 rpm 250°F	2000 rpm 250°F	3100 rpm 250°F	2000 rpm 250°F	3100 rpm 250°F
0.05	127	127	141	111	116	128	137	111	110	126	128	112	96	134	121
.06	118	114	121	116	109	119	118	111	110	120	112	116	92	132	103
.07	117	118	120	119	109	123	106	116	115	125	112	123	92	128	93
.08	125	126	131	124	119	129	111	121	116	128	116	133	97	140	97
.09	126	124	127	119	126	130	120	118	116	124	120	128	106	137	104
.10	128	122	126	115	126	129	123	113	114	123	119	123	112	135	118
.11	122	128	131	110	117	124	120	107	111	119	119	118	115	132	125
.12	117	125	---	105	112	119	118	103	107	115	120	113	116	129	124
.13	---	---	---	101	---	115	---	100	---	114	---	110	---	127	---
.14	---	---	---	98	---	110	---	99	---	109	---	108	---	123	---

Fuel-air ratio	Maximum permissible imep, percent of S-1 (or S-1A)															
	Fuel 11		85 percent fuel 11, 15 percent benzene		85 percent fuel 11, 15 percent toluene		85 percent fuel 11, 15 percent xylene		85 percent fuel 11, 15 percent isopropyl ether		60 percent fuel 11, 40 percent mixed aromatics		Fuel 11		85 percent fuel 11, 15 percent benzene	
	2000 rpm 250°F	3100 rpm 250°F	2000 rpm 250°F	3100 rpm 250°F	2000 rpm 250°F	3100 rpm 250°F	2000 rpm 250°F	3100 rpm 250°F	2000 rpm 250°F	3100 rpm 250°F	2000 rpm 250°F	3100 rpm 250°F	2000 rpm 150°F	3100 rpm 150°F	2000 rpm 150°F	3100 rpm 150°F
0.05	122	124	128	137	120	117	125	104	---	149	154	127	114	129	123	144
.06	128	113	127	118	120	110	118	114	131	127	124	112	116	130	116	141
.07	135	116	133	116	135	107	126	118	142	118	123	104	128	127	123	136
.08	143	125	141	118	148	111	140	119	146	117	137	101	135	130	133	142
.09	134	129	139	121	145	126	139	120	139	117	138	114	132	123	133	137
.10	127	127	137	126	138	133	132	129	133	132	143	118	128	118	130	132
.11	121	123	131	129	133	133	126	125	127	129	158	153	123	113	126	128
.12	115	120	125	132	129	133	122	119	122	123	159	162	119	109	123	126
.13	110	---	120	---	126	---	118	---	118	---	158	---	115	125	118	121
.14	104	---	---	---	123	---	115	---	110	---	151	---	112	---	112	---

TABLE VIII

RELATIONSHIP BETWEEN FUEL-AIR RATIO AND MAXIMUM PERMISSIBLE IMEP OF FUEL BLENDS EXPRESSED AS A PERCENTAGE OF THE STRAIGHT FUEL

Fuel-air ratio	Maximum permissible imep, percent straight fuel								
	85 percent fuel 7, 15 percent benzene	85 percent fuel 9, 15 percent benzene		85 percent fuel 10, 15 percent benzene		85 percent fuel 11, 15 percent benzene		85 percent fuel 12, 15 percent benzene	
	3100 rpm 250° F	2000 rpm 250° F	3100 rpm 250° F	2000 rpm 250° F	3100 rpm 250° F	2000 rpm 250° F	3100 rpm 250° F	2000 rpm 250° F	3100 rpm 250° F
0.05	100	116	118	114	116	105	111	120	126
.06	97	103	109	108	102	99	104	114	112
.07	101	103	97	108	98	98	100	104	101
.08	101	104	93	105	101	99	94	106	101
.09	99	109	95	105	103	104	94	107	98
.10	96	113	98	109	105	108	99	110	106
.11	106	113	102	111	107	108	105	112	108
.12	107	114	105	112	112	109	110	114	107
.13	---	114	---	114	110	109	112	115	113
.14	---	113	---	110	---	---	114	115	---

Fuel-air ratio	Maximum permissible imep, percent straight fuel									
	85 percent fuel 11, 15 percent toluene		85 percent fuel 11, 15 percent xylene		85 percent fuel 11, 15 percent isopropyl ether		60 percent fuel 11, 40 percent mixed aromatics		85 percent fuel 11, 15 percent benzene	
	2000 rpm 250° F	3100 rpm 250° F	2000 rpm 250° F	3100 rpm 250° F	2000 rpm 250° F	3100 rpm 250° F	2000 rpm 250° F	3100 rpm 250° F	2000 rpm 150° F	3100 rpm 150° F
0.05	99	94	102	84	---	120	126	103	108	112
.06	94	97	92	101	102	112	97	99	100	109
.07	100	92	94	102	105	102	91	90	96	107
.08	103	88	98	95	103	93	96	80	99	110
.09	109	98	104	93	104	91	103	88	101	111
.10	109	105	104	102	105	105	113	93	102	112
.11	110	108	105	101	105	104	131	124	102	113
.12	112	110	106	99	106	102	138	134	103	116
.13	115	113	107	101	107	104	143	---	103	97
.14	118	---	110	---	106	---	145	---	100	---

TABLE IX

RELATIONSHIP BETWEEN FUEL-AIR RATIO AND INDIVIDUAL KNOCK RATINGS FOR THE VARIOUS ENGINE CONDITIONS

[Temperatures shown refer to inlet-air temperatures]

Fuel-air ratio	Values are S-1 (or S-1A) plus recorded ml TEL per gallon														
	Fuel 7	85 percent fuel 7, 15 percent benzene	Fuel 8	Fuel 9		85 percent fuel 9, 15 percent benzene		Fuel 10		85 percent fuel 10, 15 percent benzene		Fuel 12		85 percent fuel 12, 15 percent benzene	
	3100 rpm 250°F	3100 rpm 250°F	3100 rpm 250°F	2000 rpm 250°F	3100 rpm 250°F	2000 rpm 250°F	3100 rpm 250°F	2000 rpm 250°F	3100 rpm 250°F	2000 rpm 250°F	3100 rpm 250°F	2000 rpm 250°F	3100 rpm 250°F	2000 rpm 250°F	3100 rpm 250°F
0.05	0.9	0.9	1.6	0.5	0.6	1.3	1.3	0.5	0.4	1.1	0.9	0.5	a99	1.6	0.7
.06	.9	.7	1.0	.6	.4	.8	.9	.4	.4	.8	.6	.6	a97	1.4	.1
.07	.6	.7	.9	.8	.3	.9	.2	.6	.5	1.0	.4	1.0	a97	1.2	a98
.08	1.1	1.2	1.4	1.1	.8	1.4	.4	.9	.6	1.4	.6	1.6	a99	2.1	a99
.09	1.2	1.1	1.3	1.1	1.3	1.8	.8	1.0	.6	1.4	.8	1.6	.2	2.1	.1
.10	1.7	1.3	1.6	.8	1.6	1.7	1.4	.7	.7	1.3	1.1	1.3	.5	2.1	1.0
.11	1.4	1.8	2.0	.6	1.1	1.5	1.3	.4	.7	1.1	1.2	1.1	.9	2.1	1.6
.12	.9	b1.3	---	.3	.7	1.3	.9	.2	.5	1.0	1.0	.9	.8	1.9	b1.3
.13	---	---	---	.1	---	1.0	---	0	---	.9	---	.6	---	1.7	---
.14	---	---	---	a99	---	.6	---	a99	---	.6	---	.5	---	1.5	---
Variation, ml	1.1	1.1	1.1	1.2	1.3	1.2	1.2	1.1	.3	.8	.8	1.1	1.2	.9	1.8

Fuel-air ratio	Values are S-1 (or S-1A) plus recorded ml TEL per gallon															
	Fuel 11		85 percent fuel 11, 15 percent benzene		85 percent fuel 11, 15 percent toluene		85 percent fuel 11, 15 percent xylene		85 percent fuel 11, 15 percent isopropyl ether		60 percent fuel 11, 40 percent mixed aromatics		Fuel 11		85 percent fuel 11, 15 percent benzene	
	2000 rpm 250°F	3100 rpm 250°F	2000 rpm 250°F	3100 rpm 250°F	2000 rpm 250°F	3100 rpm 250°F	2000 rpm 250°F	3100 rpm 250°F	2000 rpm 250°F	3100 rpm 250°F	2000 rpm 250°F	3100 rpm 250°F	2000 rpm 150°F	3100 rpm 150°F	2000 rpm 150°F	3100 rpm 150°F
0.05	0.9	0.8	1.2	1.3	0.8	0.6	1.1	0.2	---	2.3	b3.6	0.9	1.3	1.5	1.7	---
.06	1.2	.6	1.1	.9	.8	.4	.7	.6	1.4	1.3	1.0	.6	1.2	1.8	1.2	b3.3
.07	1.7	.6	1.5	.6	1.7	.2	1.1	.7	2.2	.7	.9	.2	1.6	1.8	1.3	2.6
.08	2.2	1.1	2.1	.7	2.4	.4	2.1	.8	2.3	.6	1.9	.0	1.9	2.1	1.8	3.0
.09	2.0	1.4	2.2	.9	2.5	1.2	2.2	.8	2.2	.6	2.2	.5	1.6	1.6	1.6	2.7
.10	1.6	1.6	2.2	1.6	2.3	2.1	1.9	1.8	2.0	2.0	2.6	1.0	1.4	1.2	1.5	2.3
.11	1.3	1.5	1.9	1.8	2.1	2.1	1.6	1.6	1.7	1.8	b3.7	b3.4	1.2	.8	1.4	1.8
.12	1.0	1.0	1.6	b2.0	1.9	b2.0	1.4	1.0	1.4	b1.2	b3.9	b4	1.0	.5	1.2	1.6
.13	.7	---	1.3	---	1.6	---	1.1	---	1.1	---	b3.8	---	.9	2.0	1.1	1.6
.14	.3	---	---	---	1.4	---	1.0	---	.7	---	3.0	---	1.0	---	1.0	---
Variation, ml	1.9	1.0	1.1	1.4	1.7	1.9	1.1	1.6	1.6	1.7	3.0	4	1.0	1.6	.8	1.7

[a]Estimated octane numbers based on assumption, one octane number equals about 0.1 ml TEL.

[b]Estimated values.

INDEX TO FIGURES

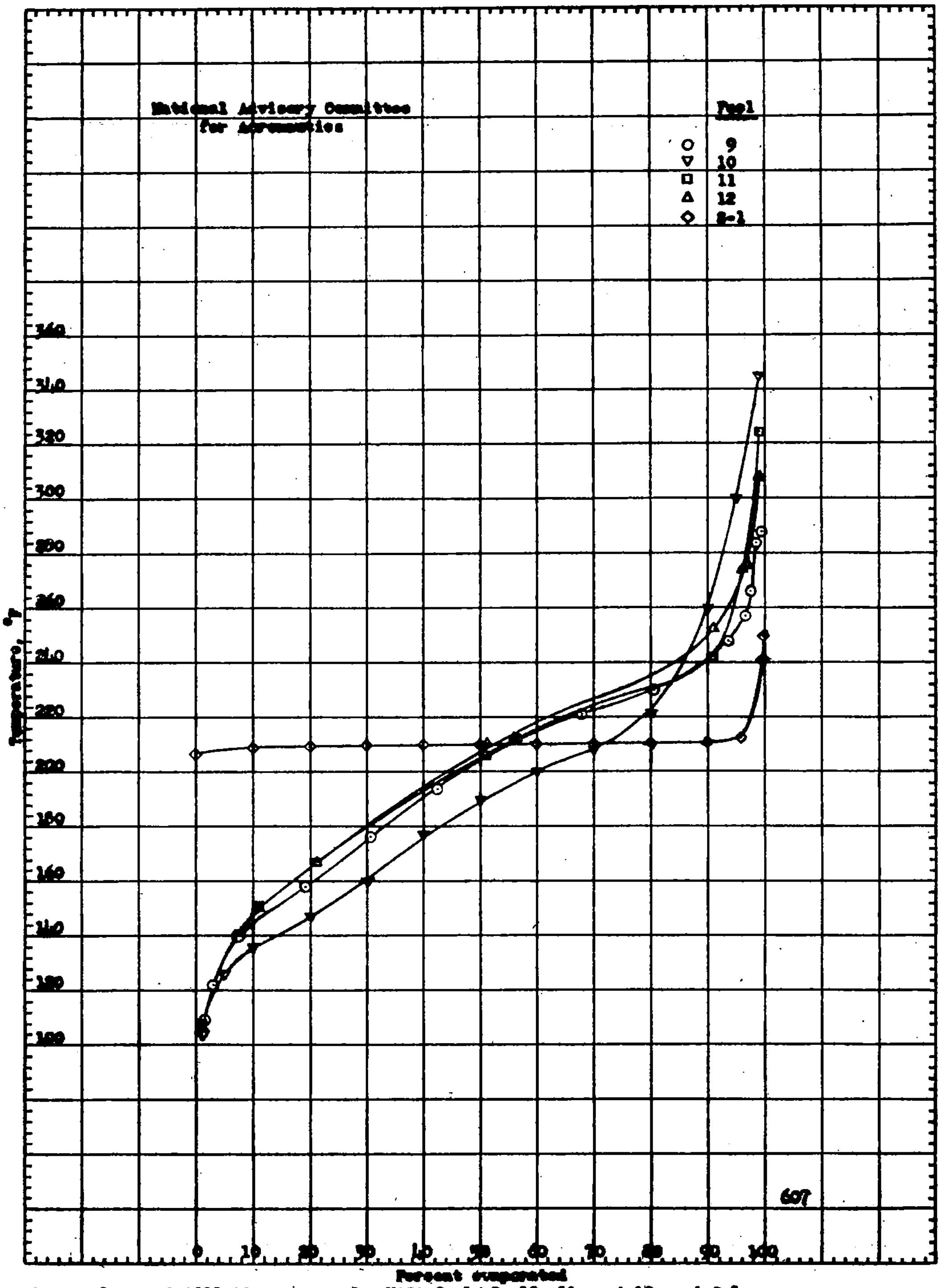
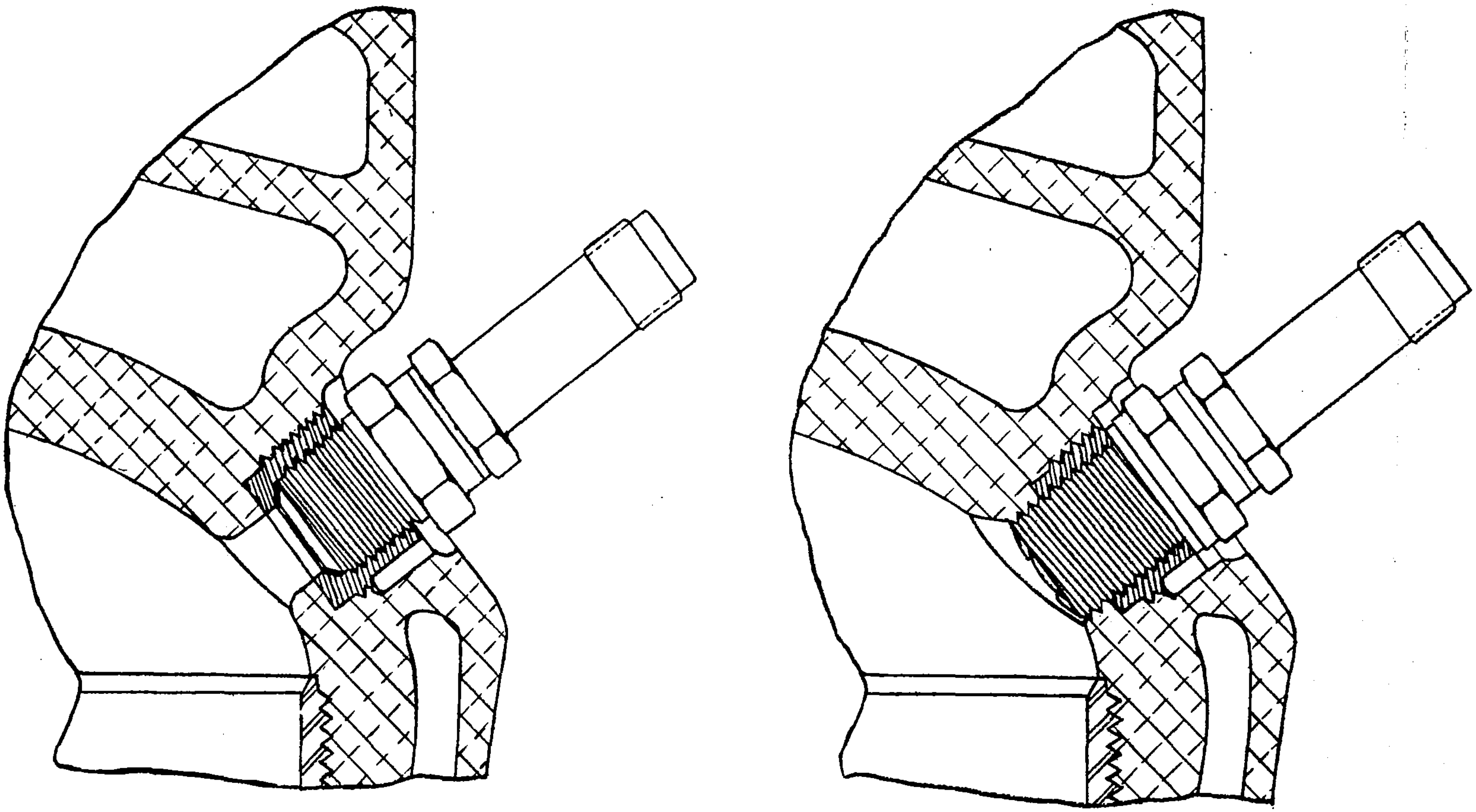


Figure 1. - Distillation curves for NACA fuels 9, 10, 11, and 12, and S-1.



(a) Bottom-seating short-reach spark plug.

(b) Top-seating long-reach spark plug.

Figure 2. - Alteration to spark plug installation; Lycoming O-1230 cylinder.

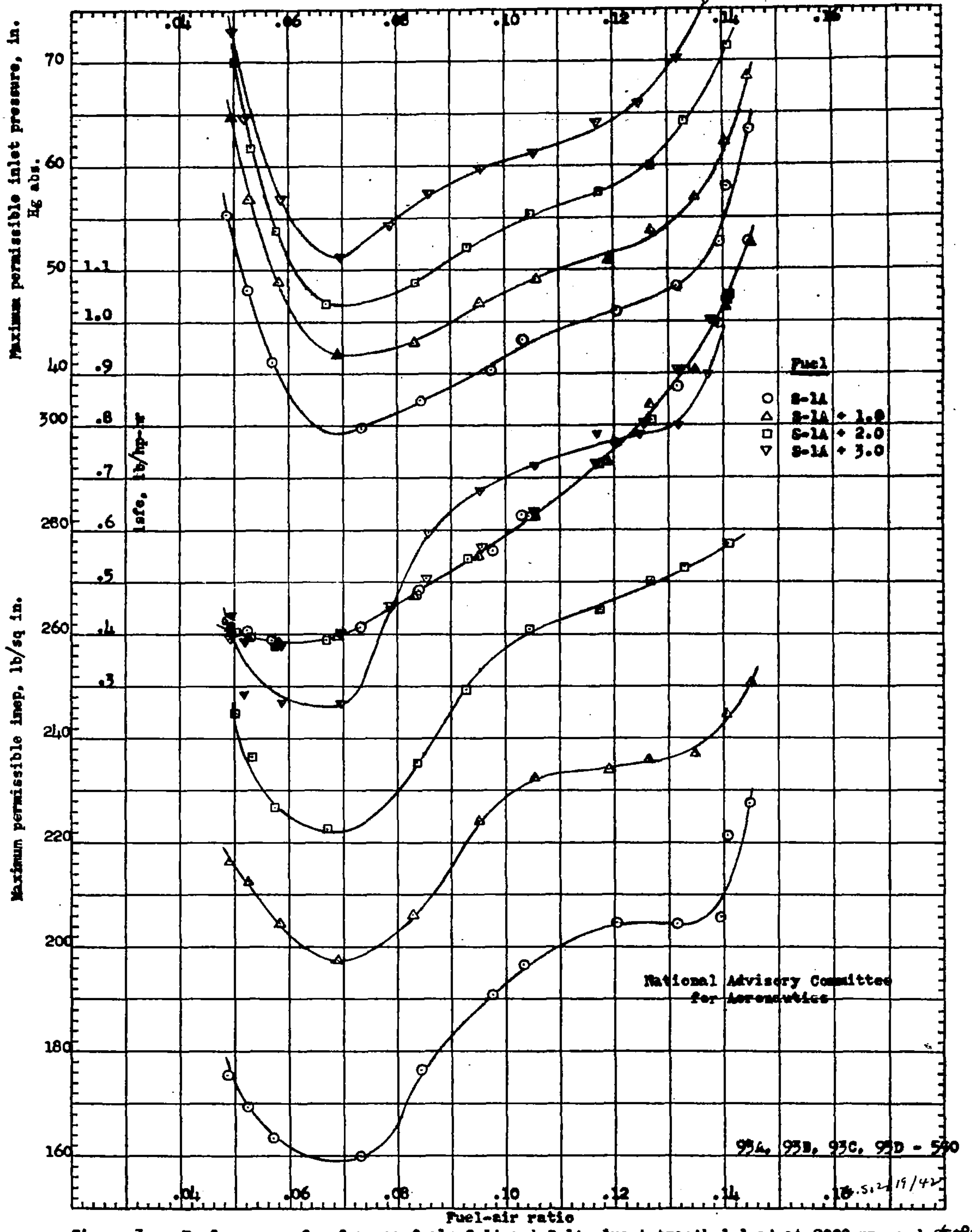


Figure 3. - Performance of reference fuels S-1A and S-1A plus tetraethyl lead at 2000 rpm and 250°F inlet-air temperature. Lycoming O-1230 cylinder; spark advance, 21°; coolant inlet temperature, 250°F; compression ratio, 7.0.

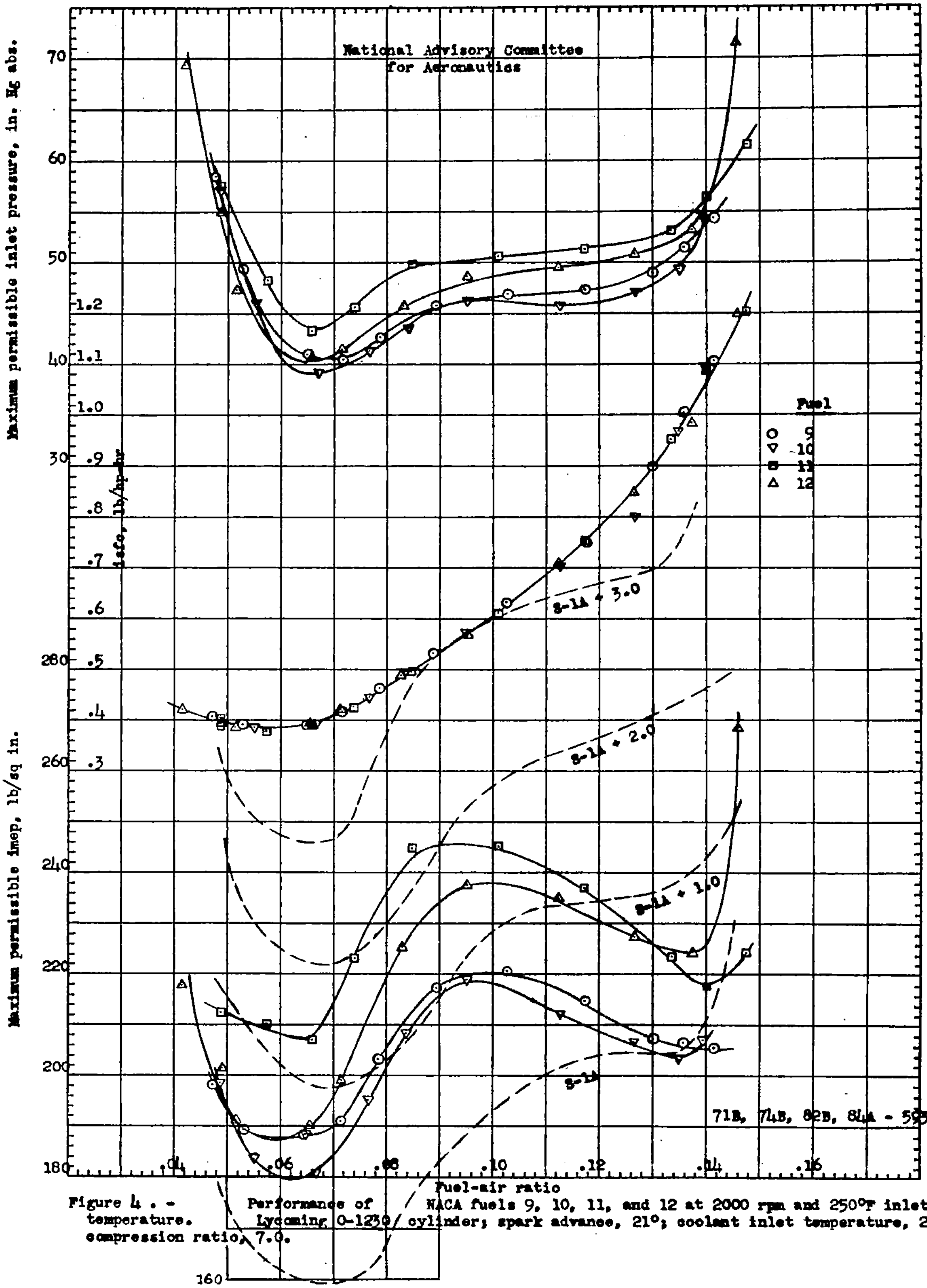


Figure 4. - Performance of NACA fuels 9, 10, 11, and 12 at 2000 rpm and 250°F inlet-air temperature. Lycoming O-1230 cylinder; spark advance, 21°; coolant inlet temperature, 250°F; compression ratio, 7.0.

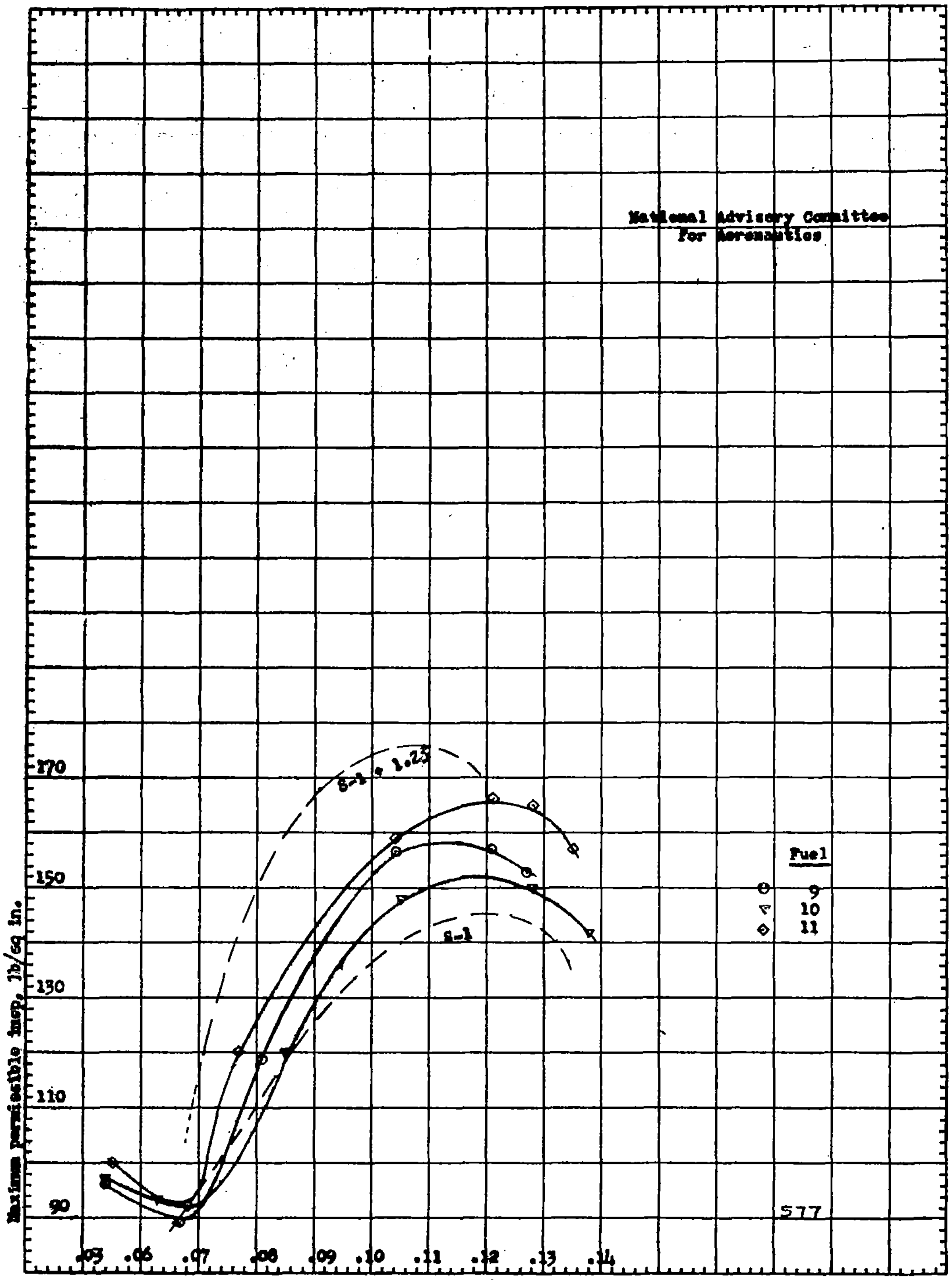


Figure 5. - Comparative performance of NACA fuels 9, 10, and 11 by 3-C Method. 2-5/8-inch C.F.R. engine; engine speed, 1800 rpm; spark advance, 45°; coolant temperature, 375°F; compression ratio, 7.0; intake-air temperature, 225°F. Data from Esso Laboratories.

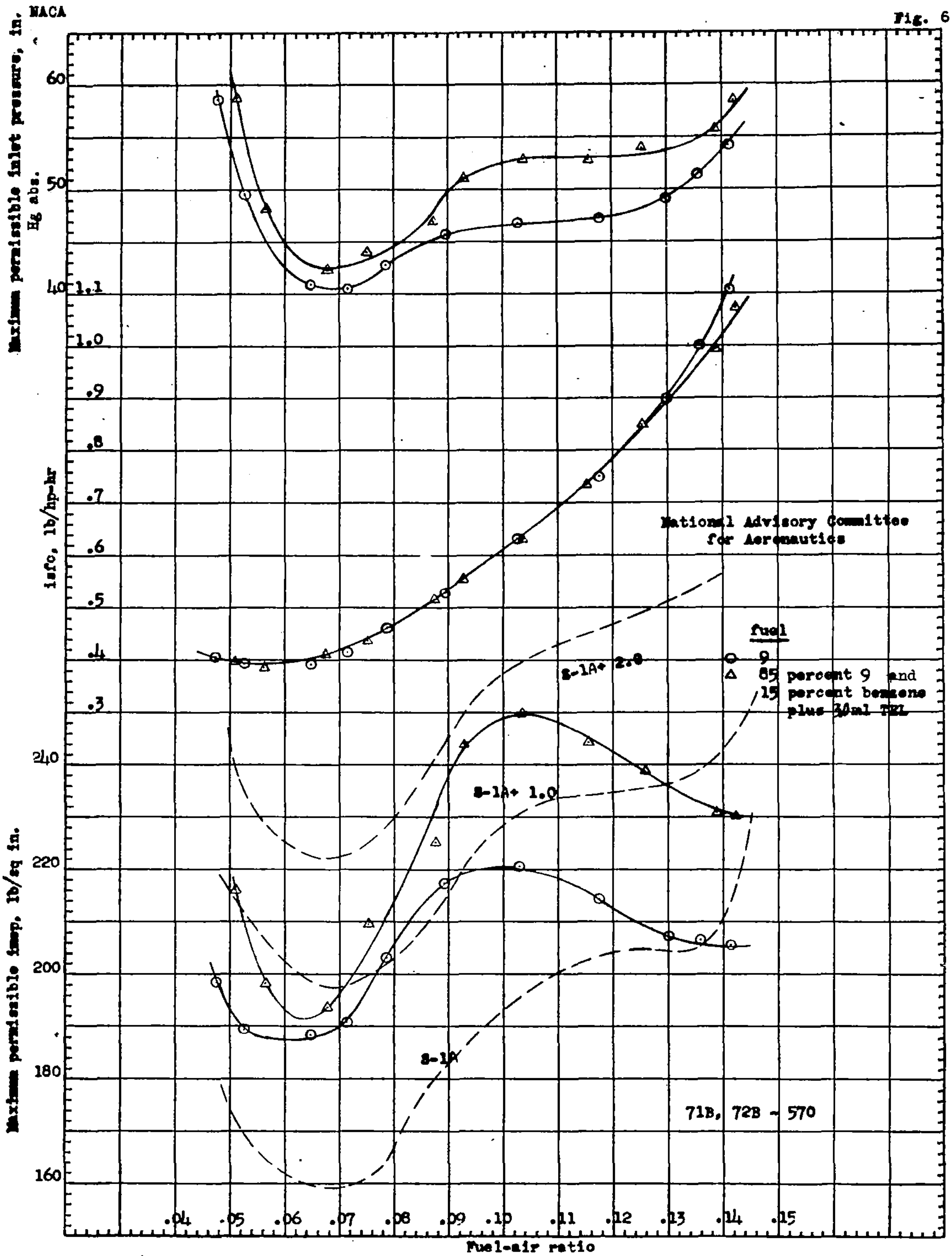


Figure 6. - Performance of NACA fuel 9 with and without addition of leaded benzene at 2000 rpm and 250°F inlet-air temperature. Lycoming O-1230 cylinder; spark advance, 21°; coolant inlet temperature, 250°F; compression ratio, 7.0.

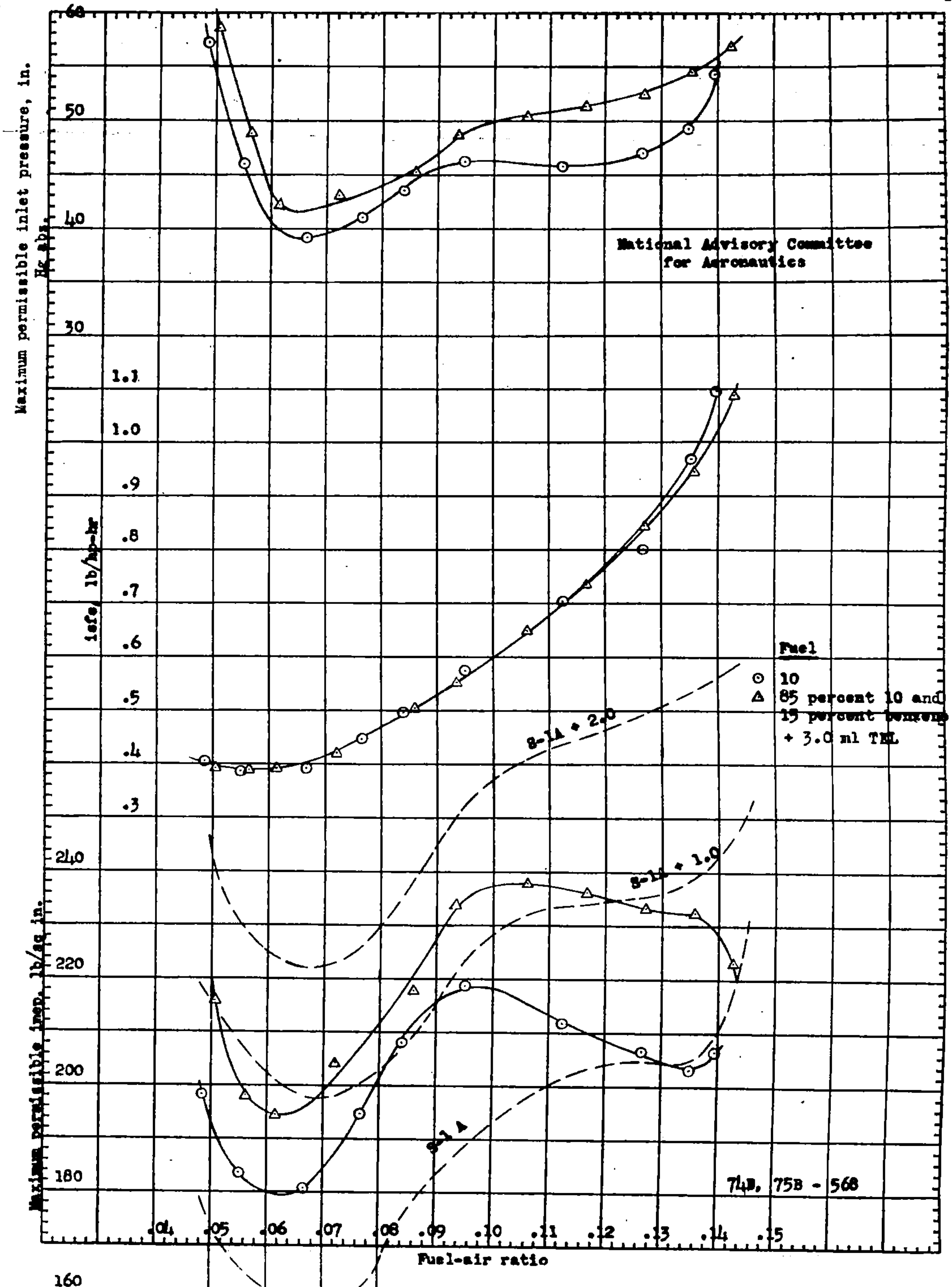


Figure 7. - Performance of NACA fuel 10 with and without addition of leaded benzene at 2000 rpm and 250°F inlet-air temperature. Lycoming O-1230 cylinder; spark advance, 21°; coolant inlet temperature, 250°F; compression ratio, 7.0.

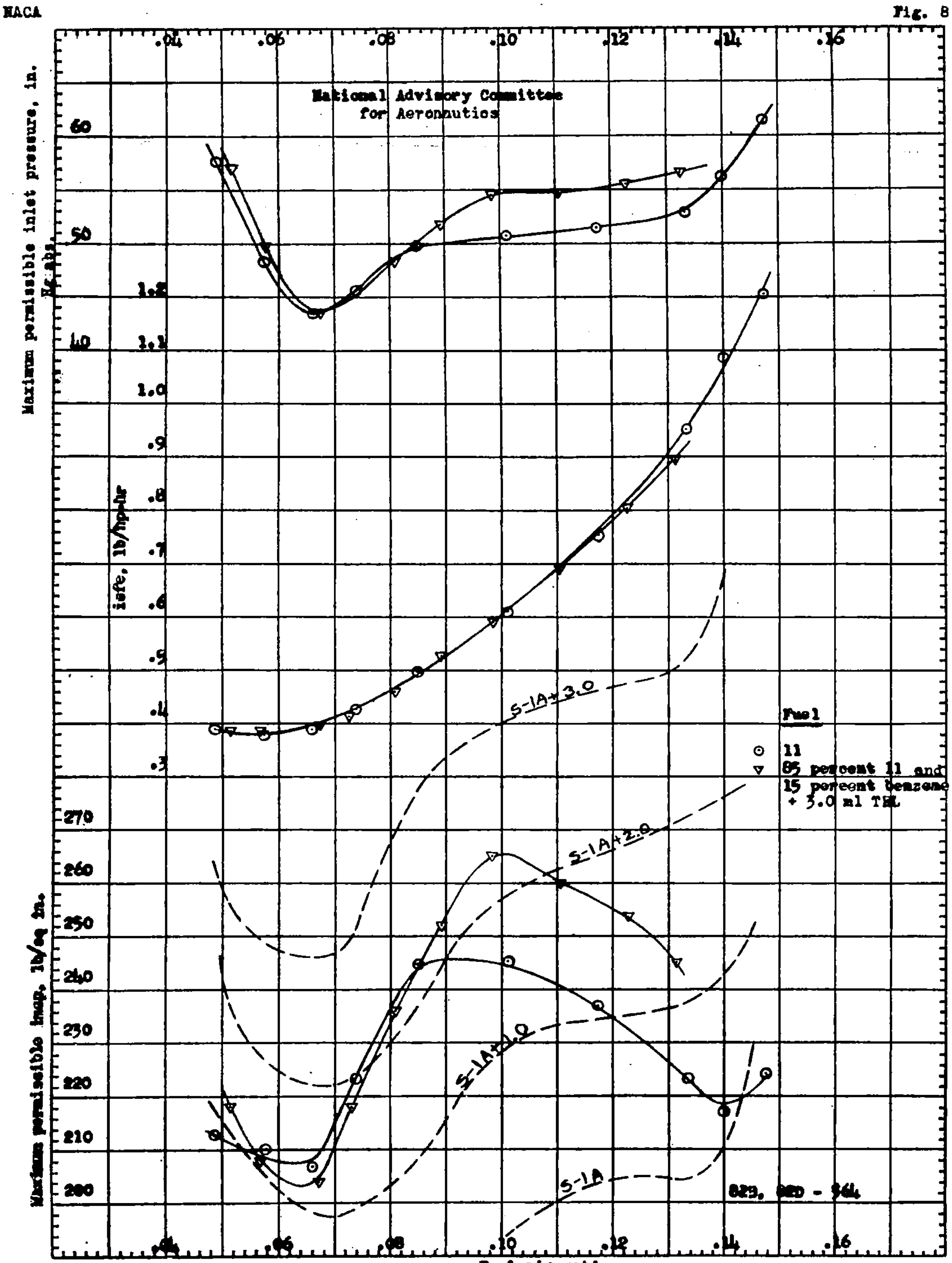


Figure 8 . - Performance of NACA fuel 11 with and without addition of leaded benzene at 2000 rpm and 250°F inlet-air temperature. Lycoming O-1230 cylinder; spark advance, 21°; coolant inlet temperature, 250°F; compression ratio, 7.0.

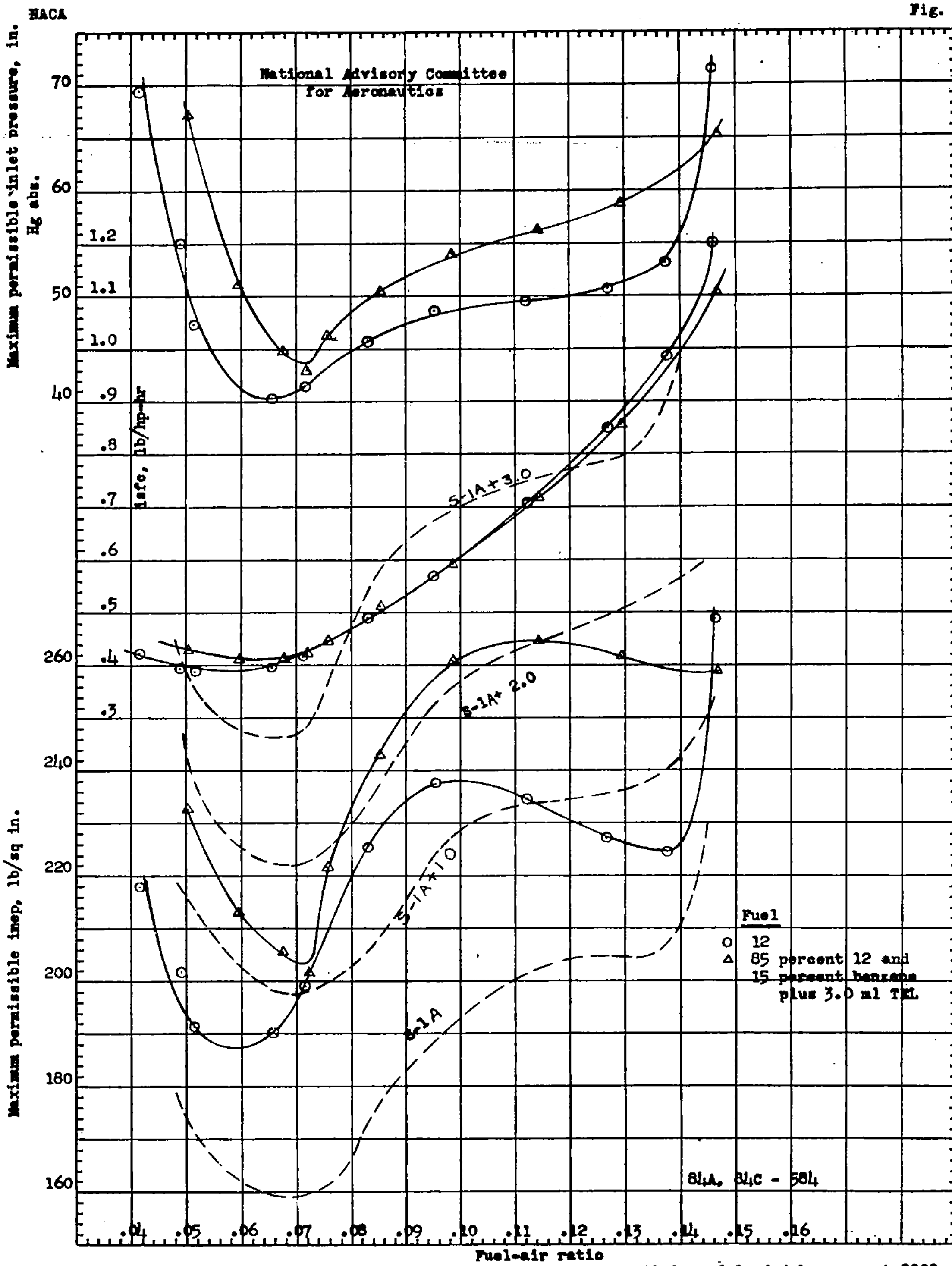


Figure 9. - Performance of NACA fuel 12 with and without addition of leaded benzene at 2000 rpm and 250°F inlet-air temperature. Lycoming O-1230 cylinder; spark advance, 21°; coolant inlet temperature, 250°F; compression ratio, 7.0.

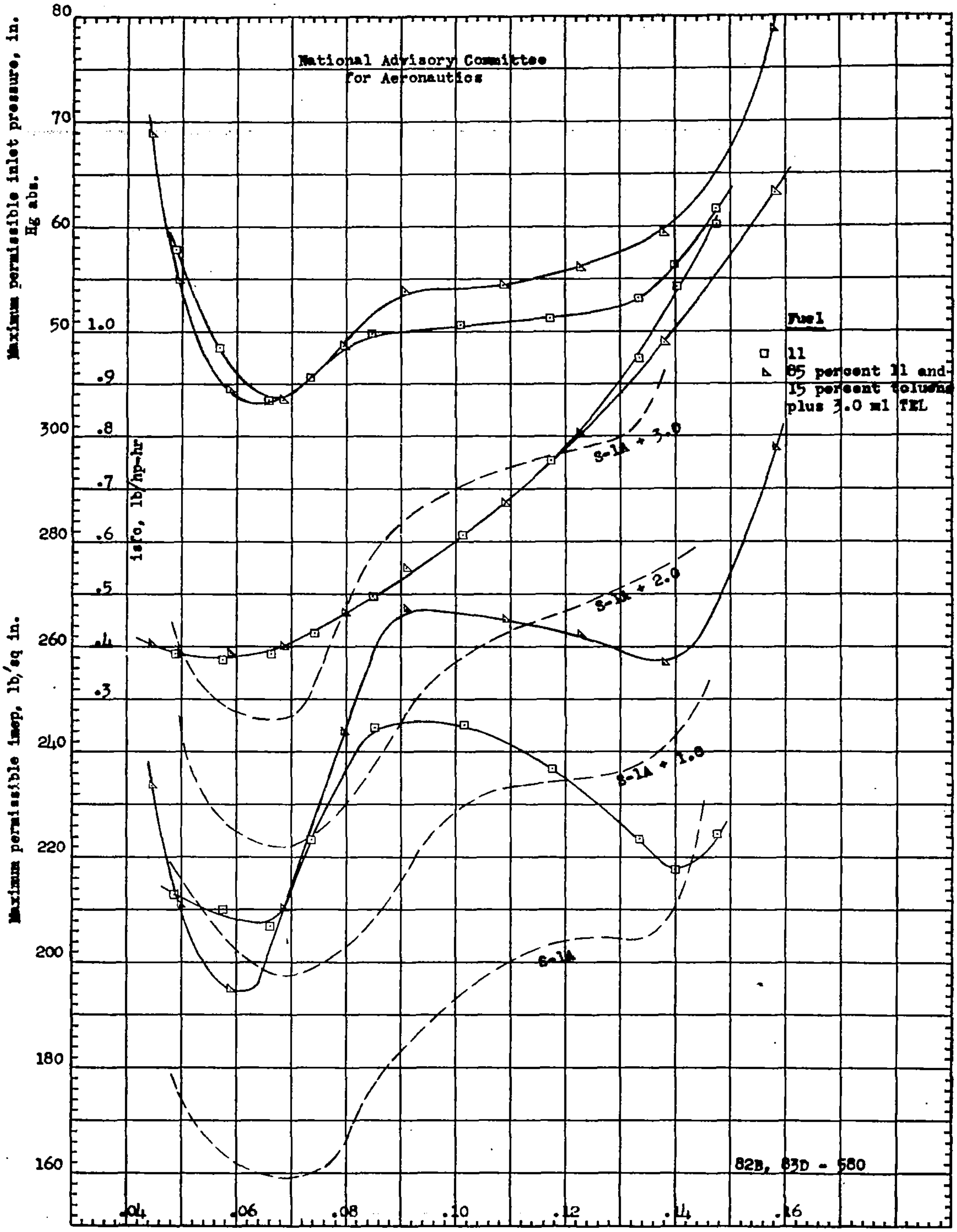


Figure 10 . - Performance of NACA fuel 11 with and without addition of leaded toluene at 2000 rpm and 250°F inlet-air temperature. Lycoming O-1230 cylinder; spark advance, 21°; coolant inlet temperature, 250°F; compression ratio, 7.0.

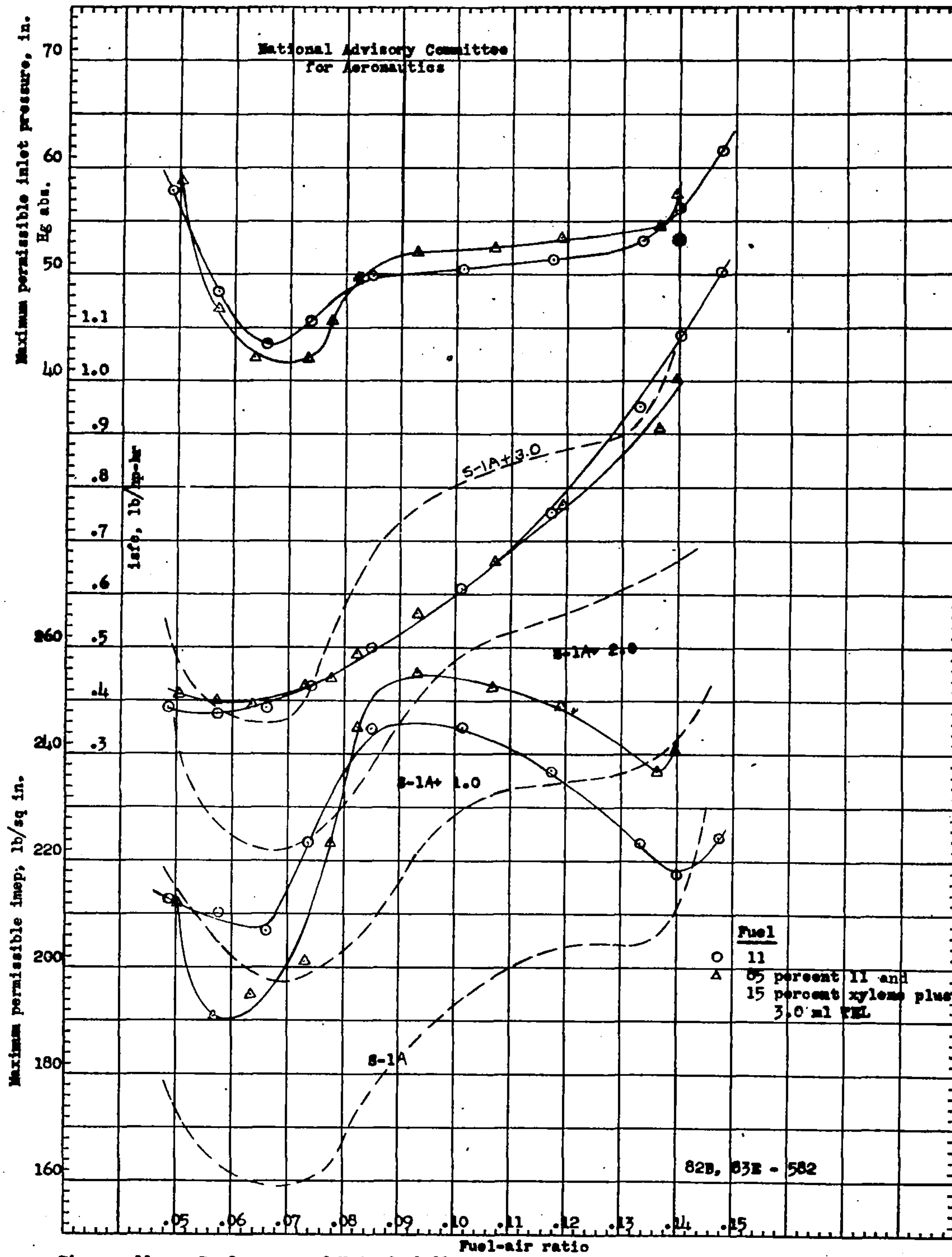


Figure 11. - Performance of NACA fuel 11 with and without addition of leaded xylene at 2000 rpm and 250°F inlet-air temperature. Lycoming O-1230 cylinder; spark advance, 21°; coolant inlet temperature, 250°F; compression ratio, 7.0.

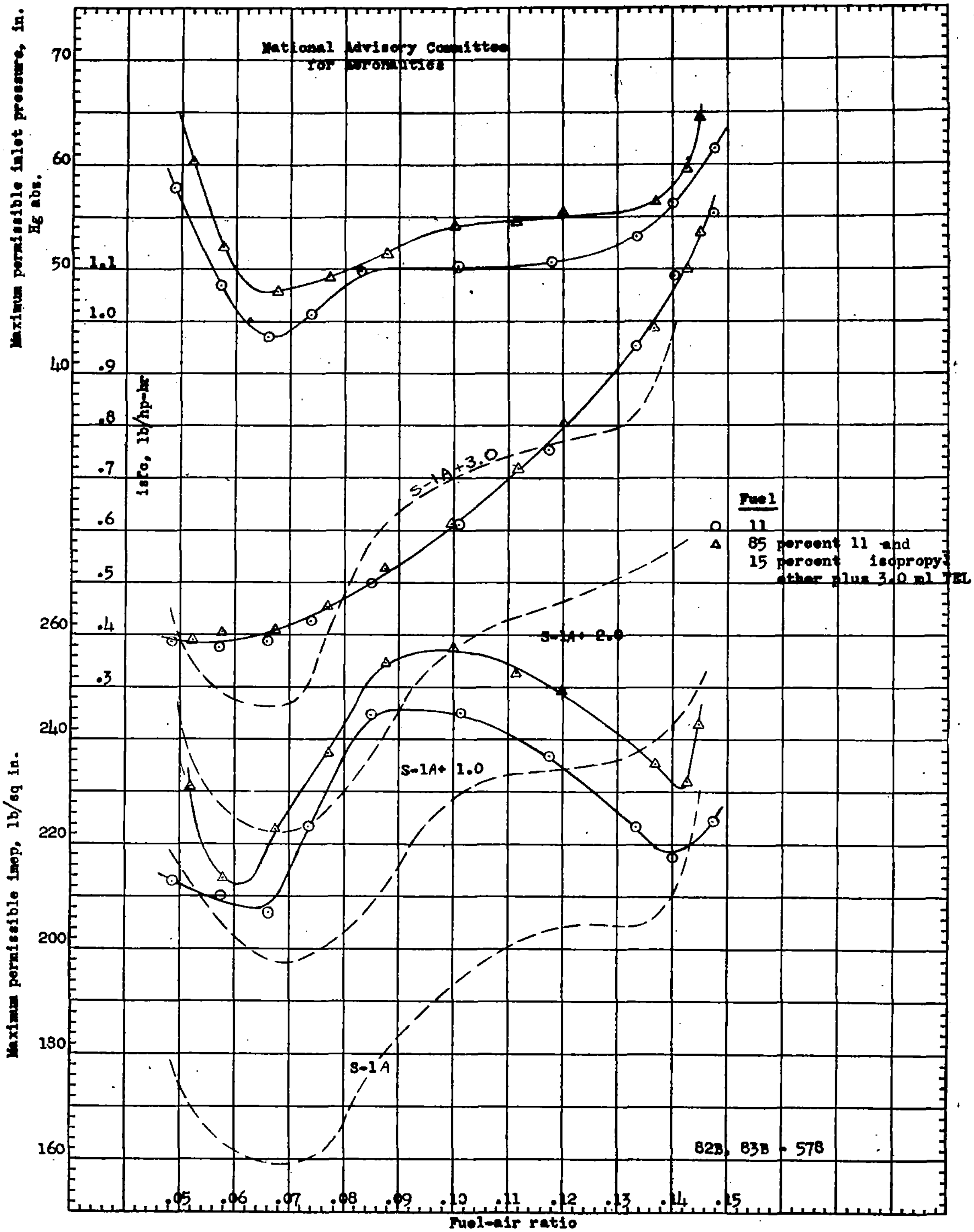


Figure 12 . - Performance of NACA fuel 11 with and without addition of leaded isopropyl ether at 2000 rpm and 250°F inlet-air temperature. Lycoming O-1230 cylinder; spark advance, 21°; coolant inlet temperature, 250°F; compression ratio, 7.0.

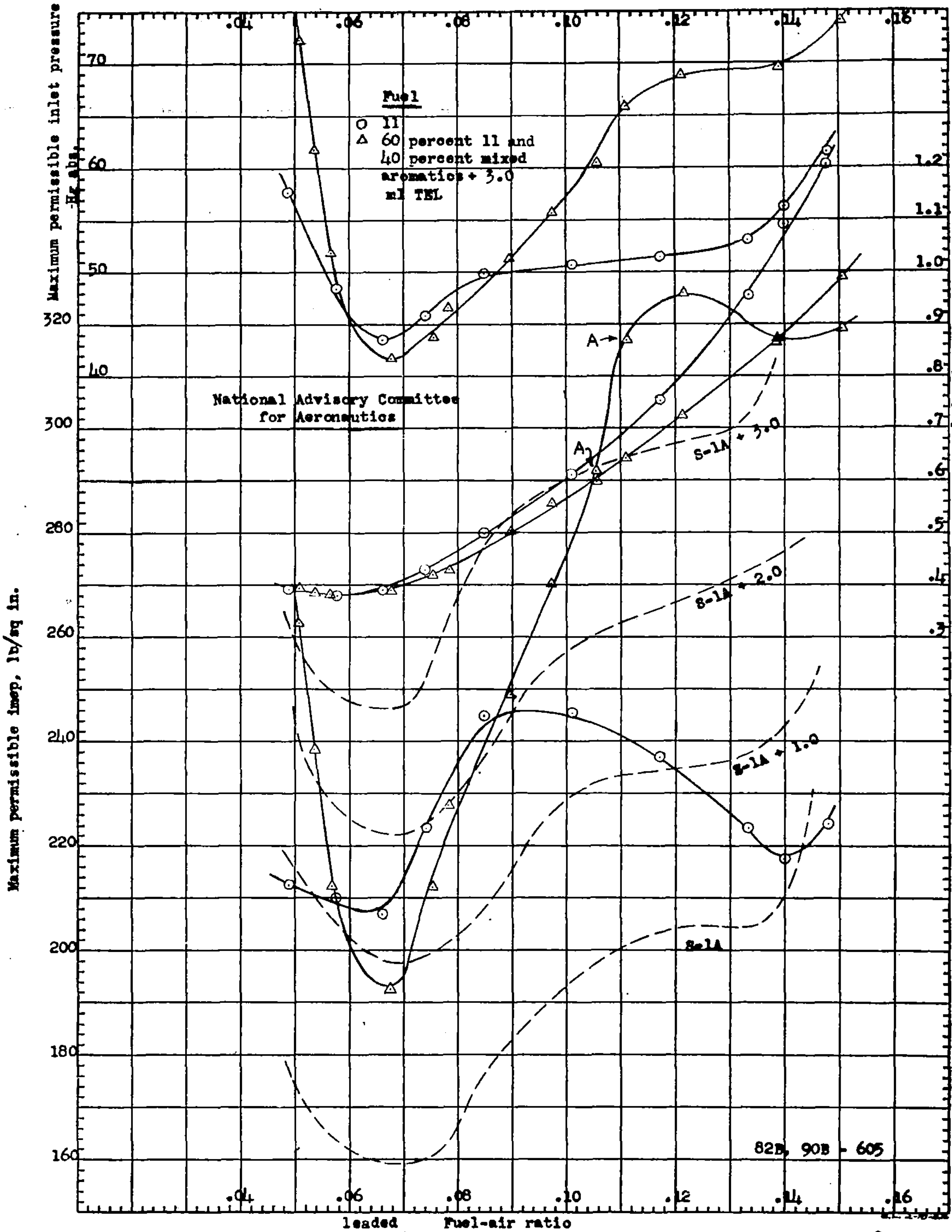


Figure 13. - Effect of addition of leaded mixed aromatics on NACA fuel 11 at 2000 rpm and 250°F inlet-air temperature. Lycoming O-1230 cylinder; spark advance, 21°; coolant inlet temperature, 250°F; compression ratio, 7.0.

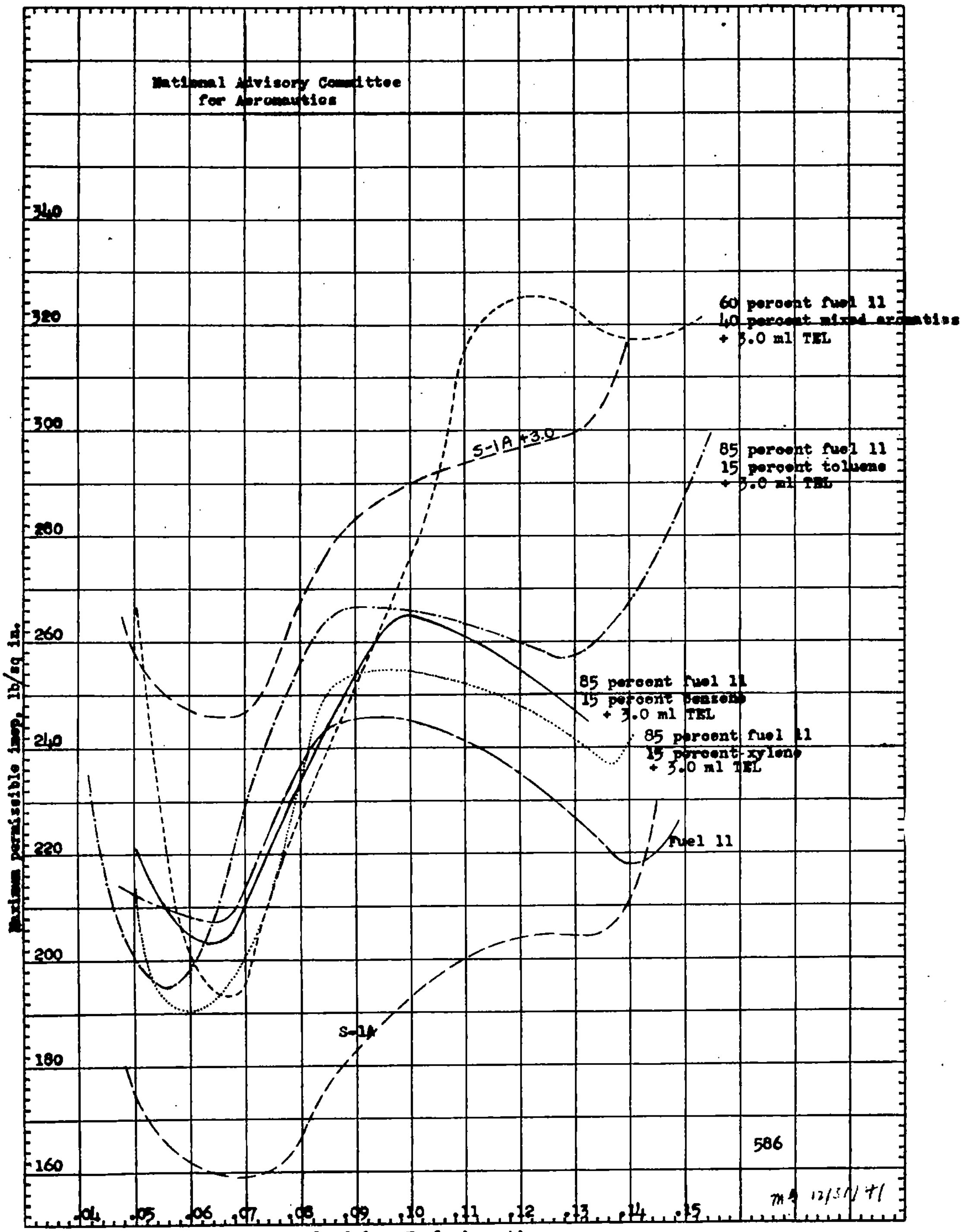


Figure 14. - Effect of various leaded aromatic additives on performance of NACA fuel 11 at 2000 rpm and 250°F inlet-air temperature. Lycoming O-1230 cylinder; spark advance, 21°; coolant inlet temperature, 250°F; compression ratio, 7.0.

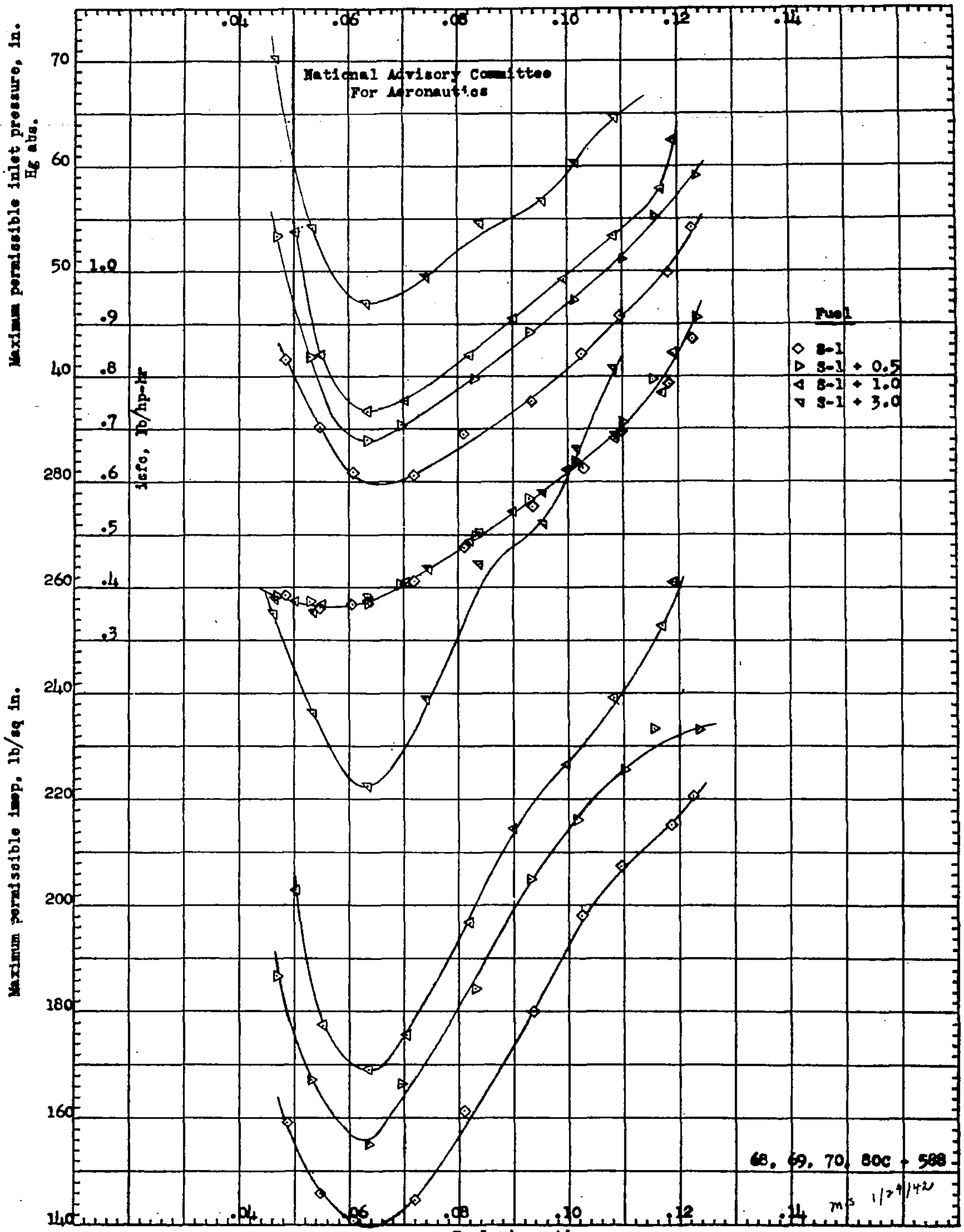


Figure 15. - Performance of reference fuels S-1 and S-1 plus tetraethyl lead at 3100 rpm and 250°F inlet-air temperature. Lycoming O-1230 cylinder; spark advance, 29°; coolant inlet temperature, 250°F; compression ratio, 7.0.

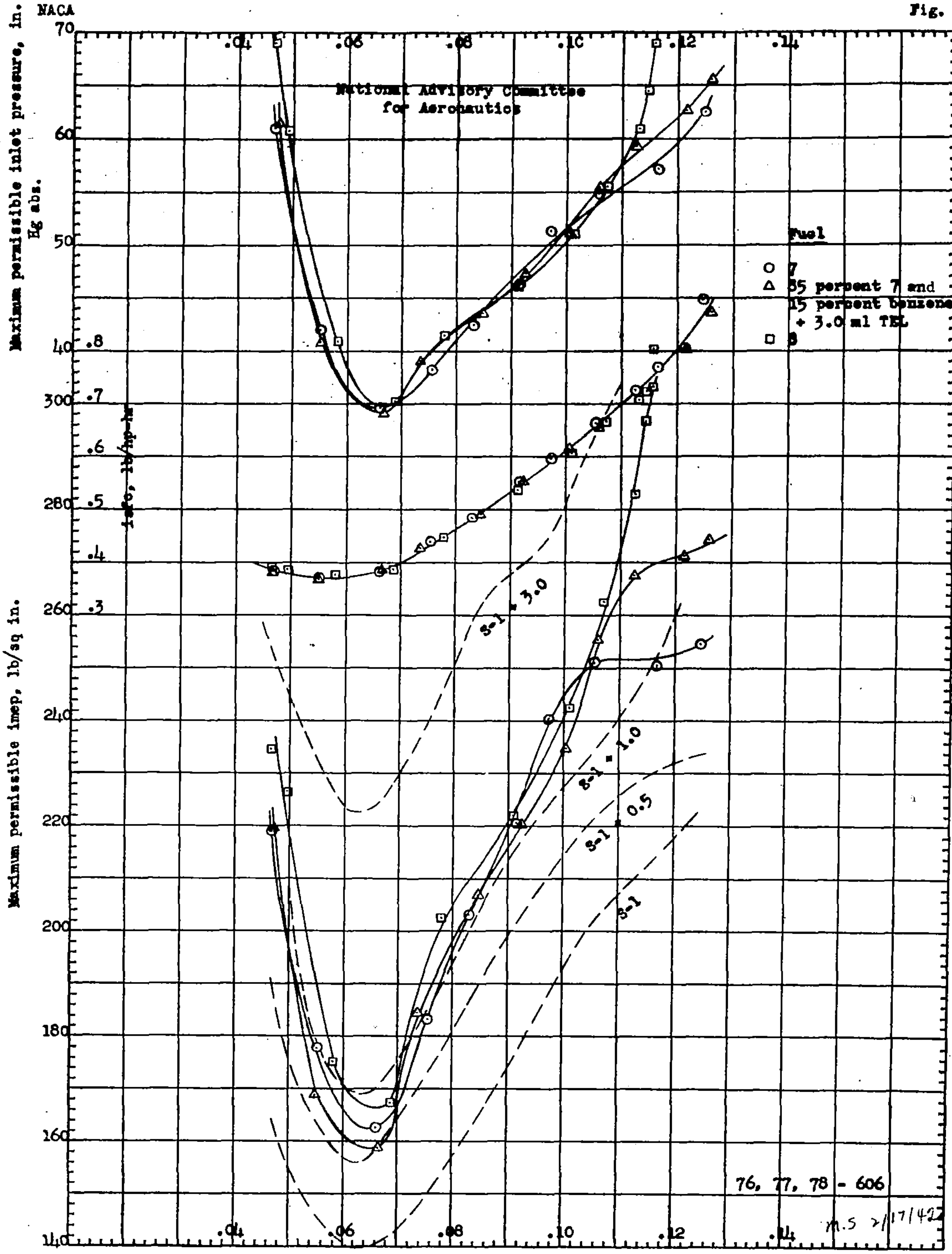


Figure 16 . - Performance of NACA fuel 7 with and without addition of leaded benzene and NACA fuel 8 at 3100 rpm and 250°F inlet-air temperature. Lycoming O-1230 cylinder; spark advance, 29°; coolant inlet temperature, 250°F; compression ratio, 7.0.

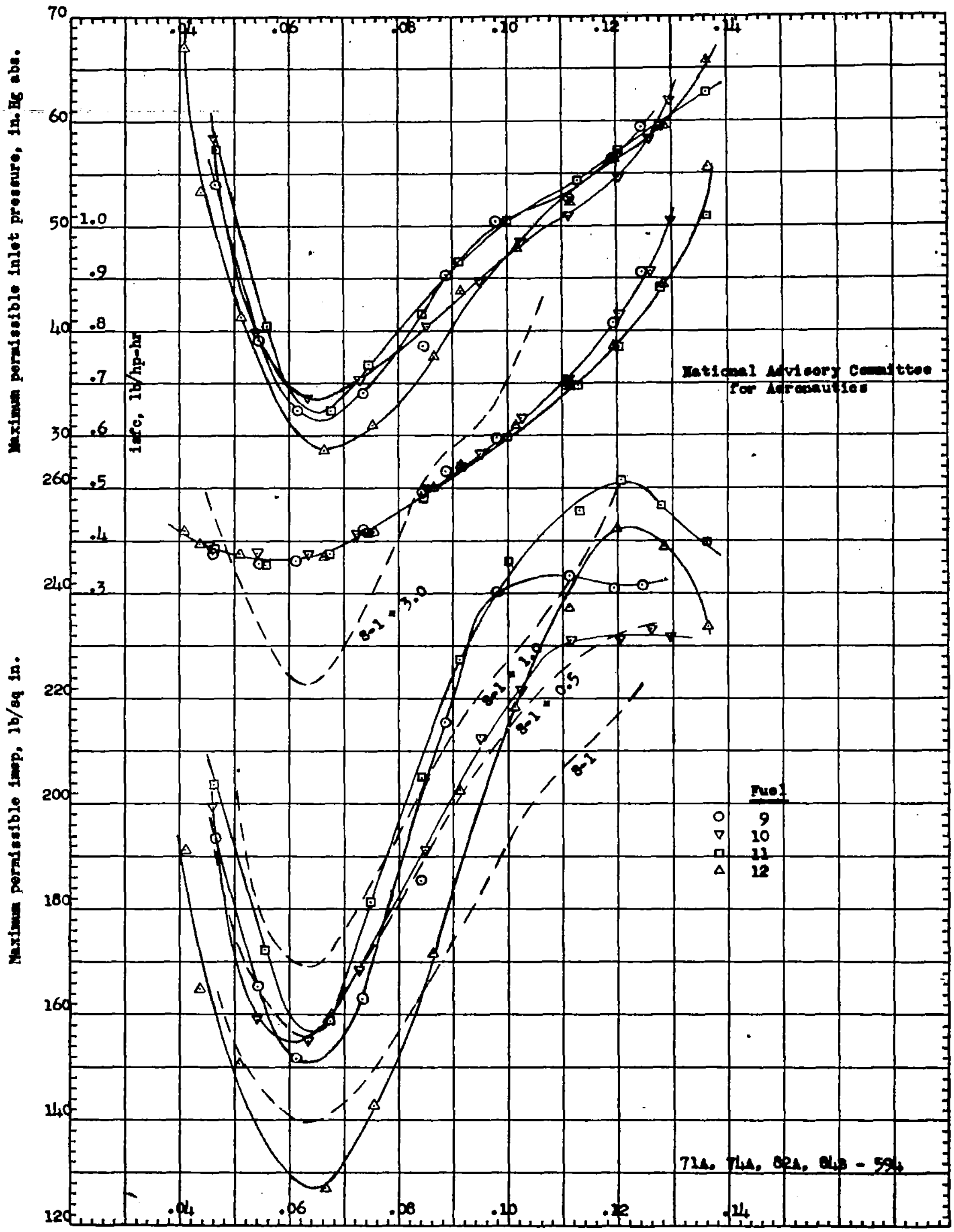


Figure 17. - Comparison of performances of NACA fuels 9, 10, 11 and 12 at 3100 rpm and 250°F inlet-air temperature. Lycoming O-1230 cylinder; spark advance, 29°; coolant inlet temperature, 250°F; compression ratio, 7.0.

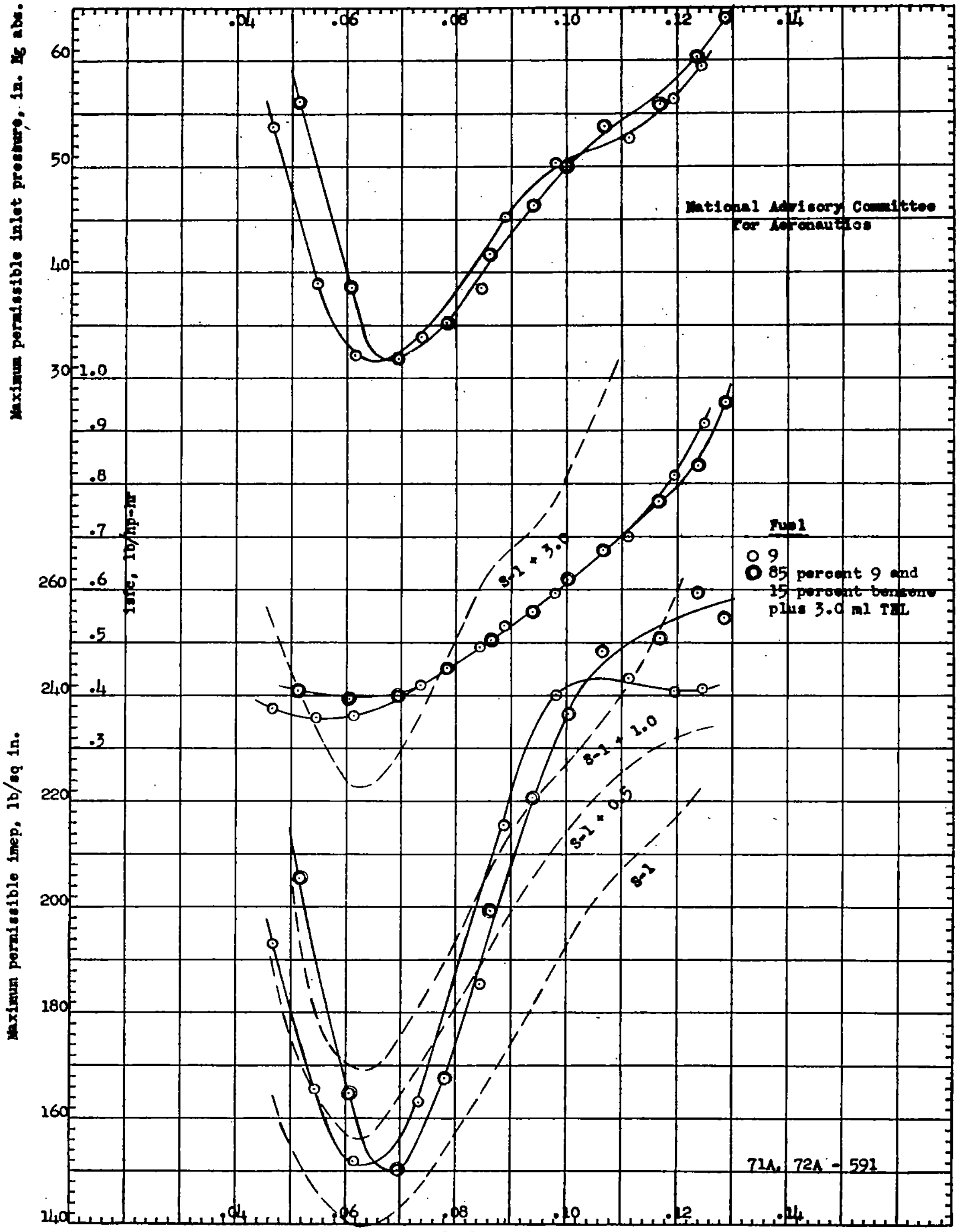


Figure 18 . - Performance of NACA fuel 9 with and without addition of leaded benzene at 3100 rpm and 250°F inlet-air temperature. Lycoming O-1230 cylinder; spark advance, 29°; coolant inlet temperature, 250°F; compression ratio, 7.0.

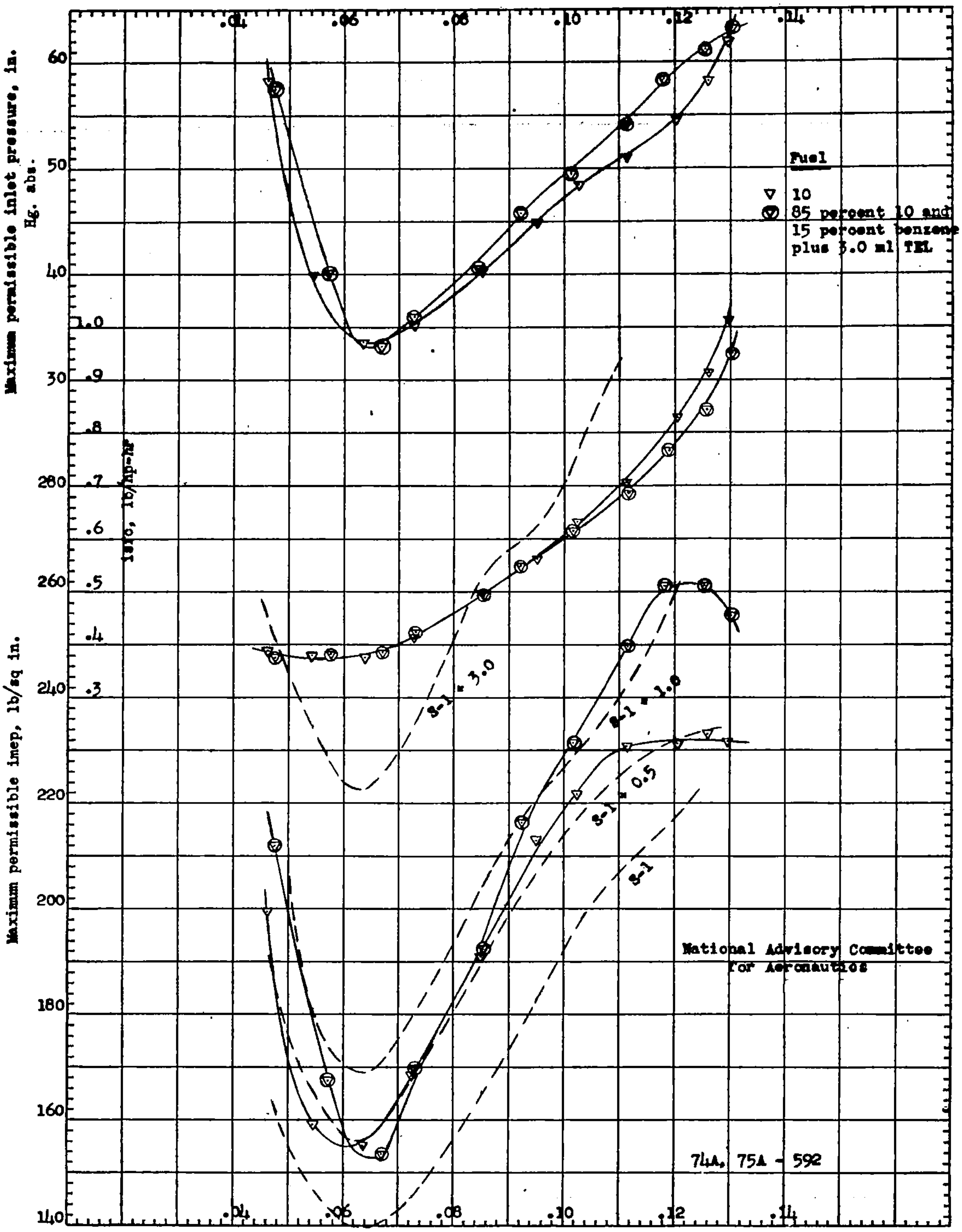


Figure 19 . - Performance of NACA fuel 10 with and without addition of leaded benzene at 3100 rpm and 250°F inlet-air temperature. Lycoming O-1230 cylinder; spark advance, 29°; coolant inlet temperature, 250°F; compression ratio, 7.0.

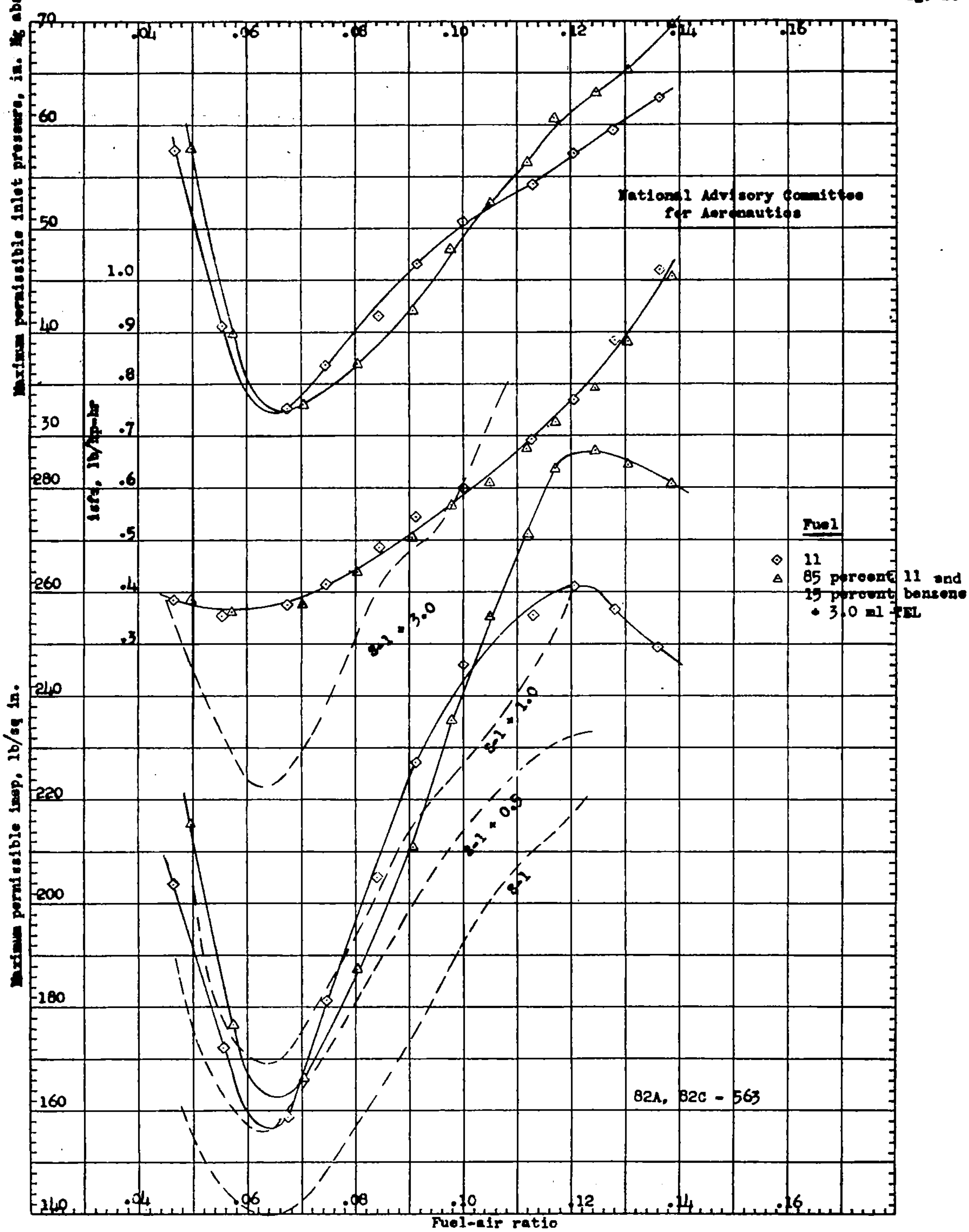


Figure 20. - Performance of NACA fuel 11 with and without addition of leaded benzene at 3100 rpm and 250 F inlet-air temperature. Lycoming O-1230 cylinder; spark advance, 29°; coolant inlet temperature, 250°F; compression ratio, 7.0.

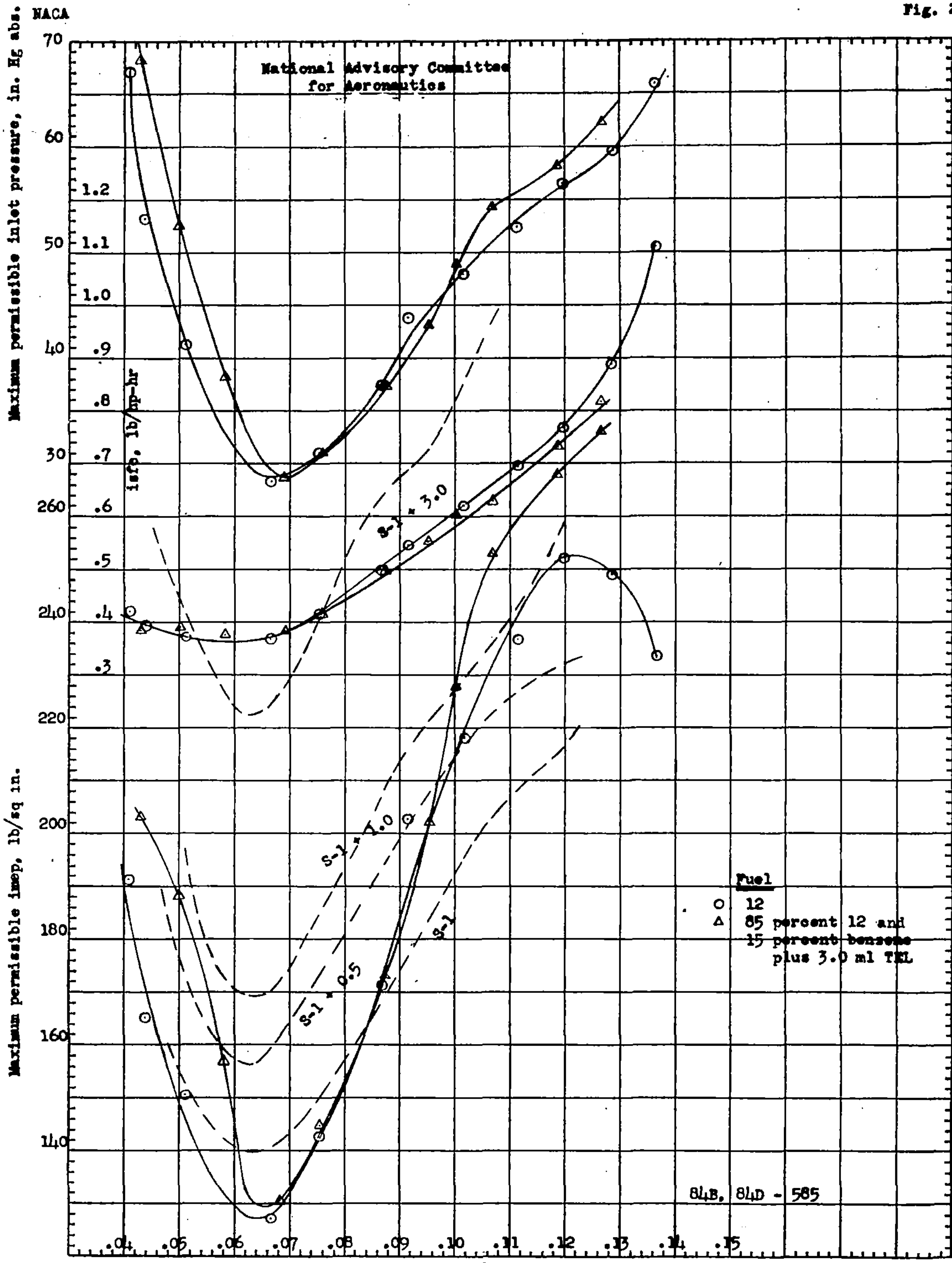


Figure 21. - Performance of NACA fuel 12 with and without addition of leaded benzene at 3100 rpm and 250°F inlet-air temperature. Lycoming O-1230 cylinder; spark advance, 29°; coolant inlet temperature, 250°F; compression ratio, 7.0.

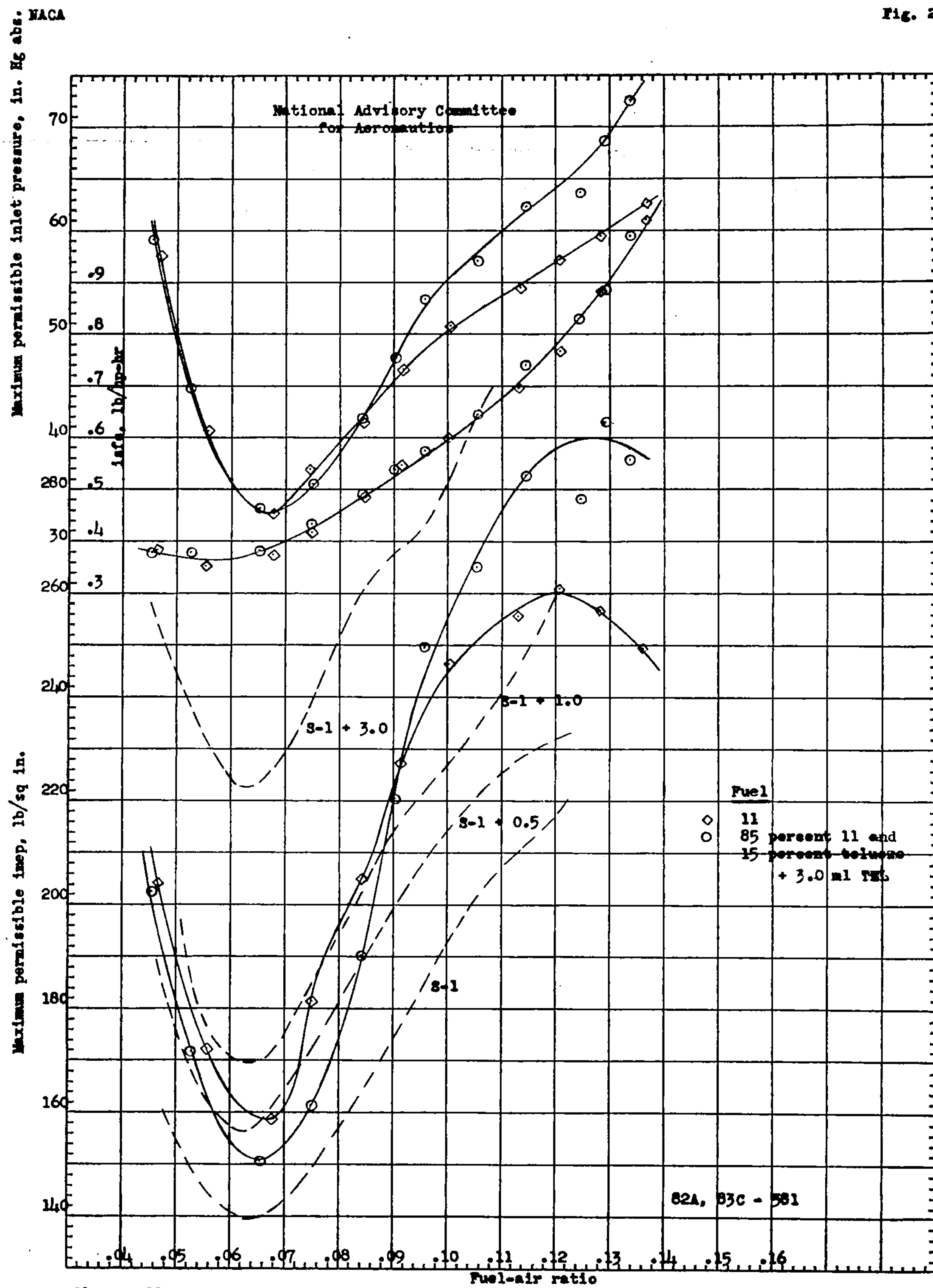


Figure 22. - Performance of NACA fuel 11 with and without addition of leaded toluene at 3100 rpm and 250°F inlet-air temperature. Lycoming O-1230 cylinder; spark advance, 29°; coolant inlet temperature, 250°F; compression ratio, 7.0.

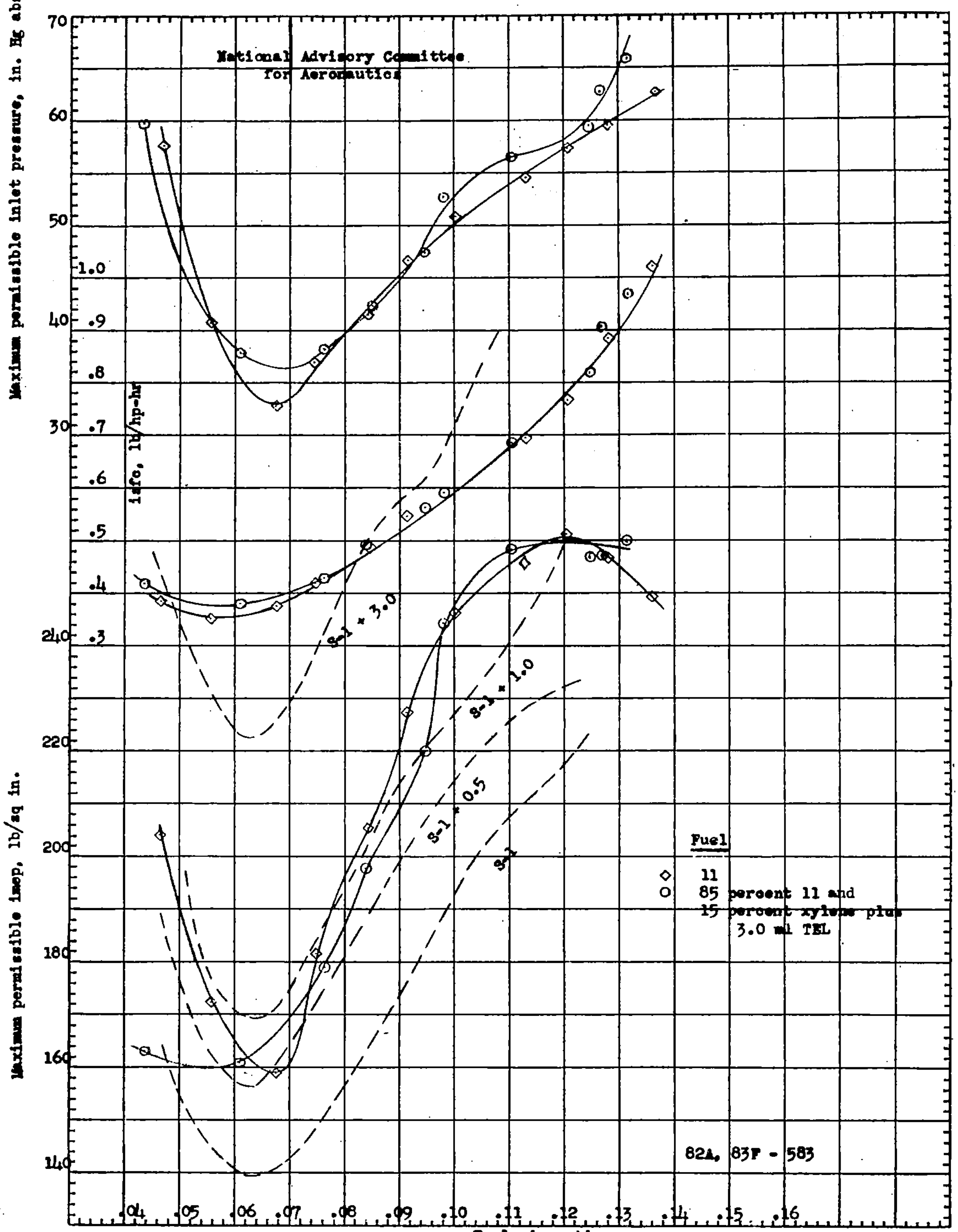


Figure 23. - Performance of NACA fuel 11 with and without addition of leaded xylene at 3100 rpm and 250°F inlet-air temperature. Lycoming O-1230 cylinder; spark advance, 29°; coolant inlet temperature, 250°F; compression ratio, 7.0.

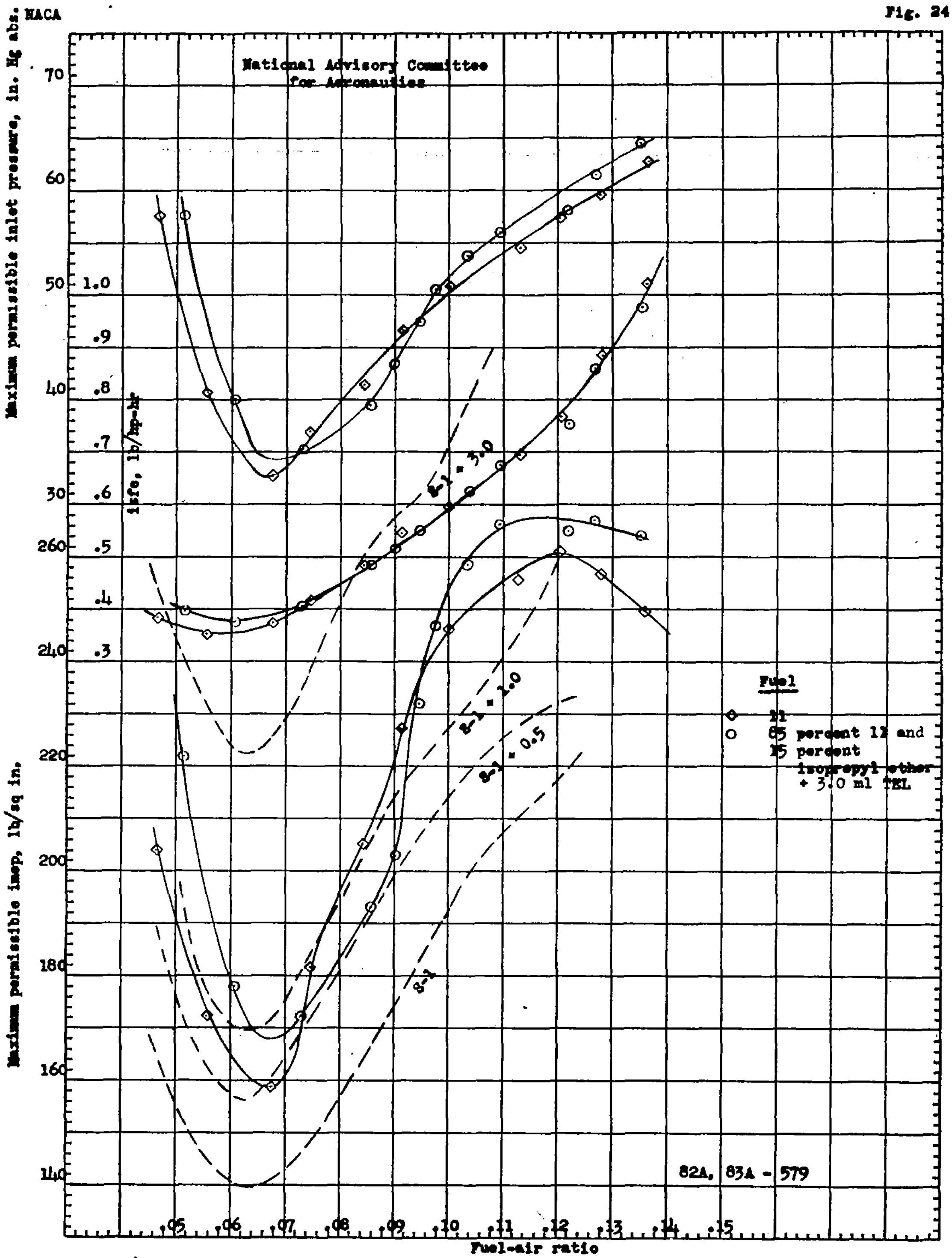


Figure 24. - Performance of NACA fuel 11 with and without addition of leaded isopropyl ether at 3100 rpm and 250°F inlet-air temperature. Lycoming O-1230 cylinder; spark advance, 29°; coolant inlet temperature, 250°F; compression ratio, 7.0.

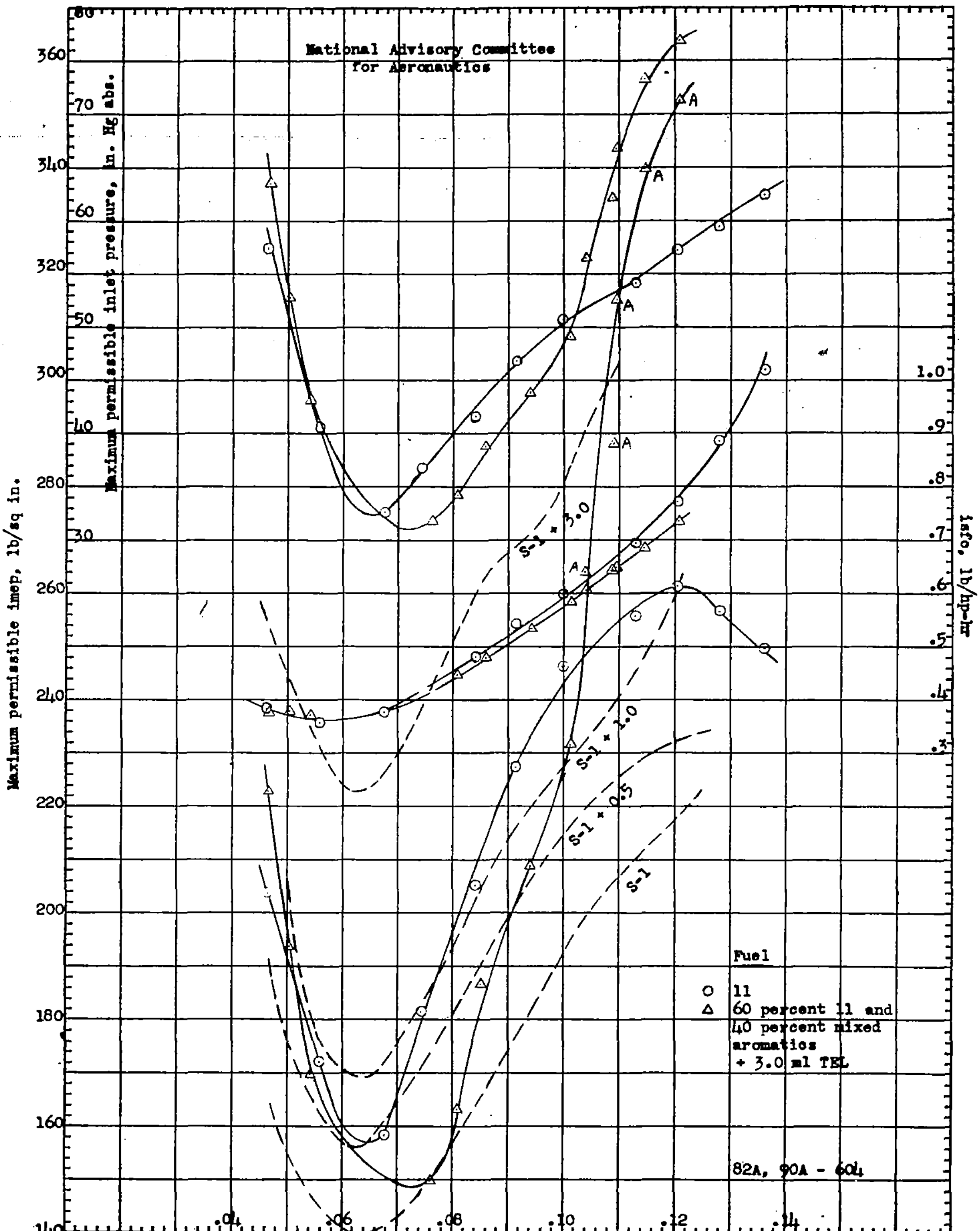


Figure 25. - Effect of addition of mixed aromatics on NACA fuel 11 at 3100 rpm and 250°F inlet-air temperature. Lycoming O-1230 cylinder; spark advance, 29°; coolant inlet temperature, 250°F; compression ratio, 7.0.

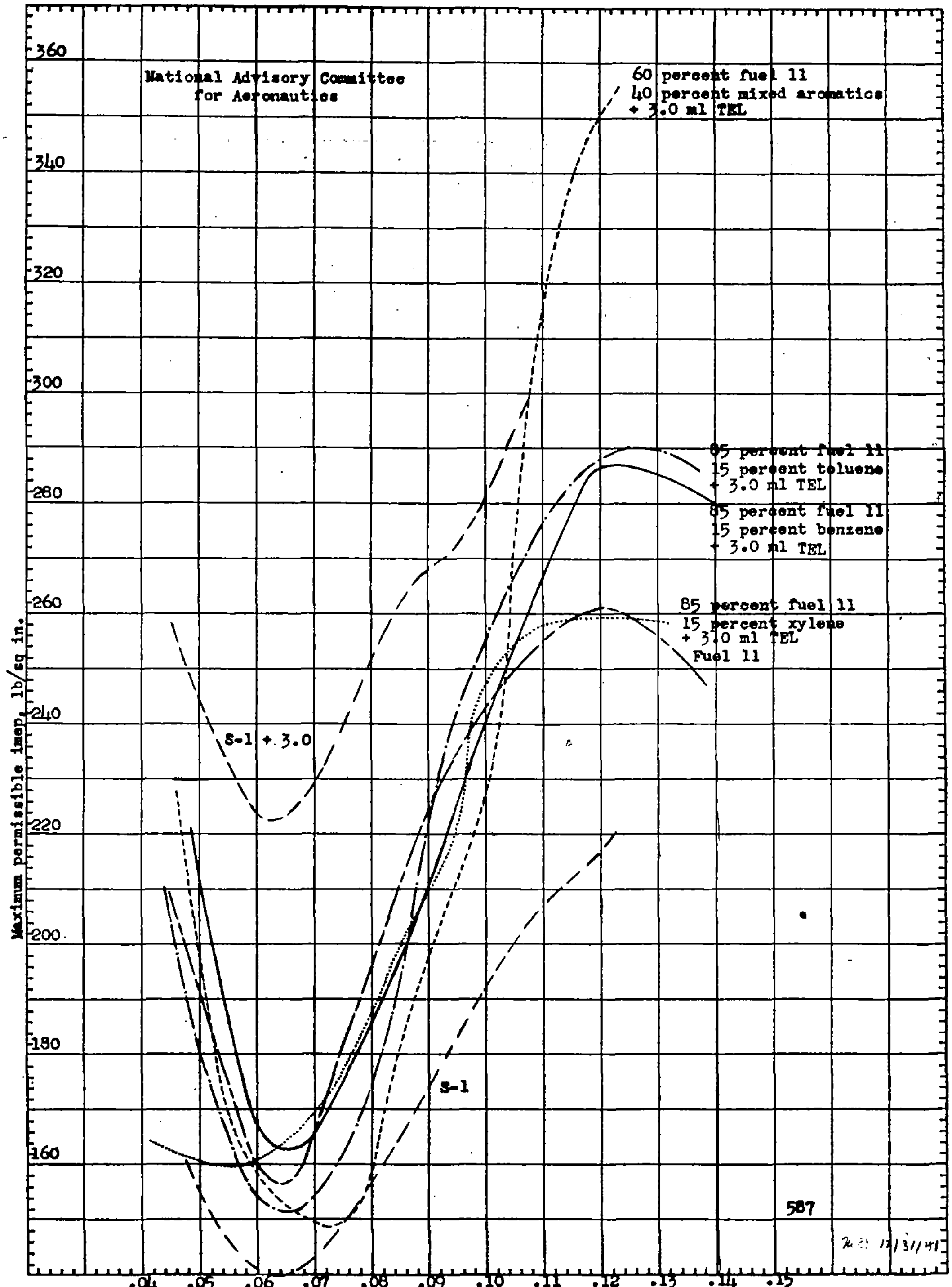


Figure 26. - Effect of various/aromatic additives on performance of NACA fuel 11 at 3100 rpm and 250°F inlet-air temperature. Lycoming O-1230 cylinder; spark advance, 29°; coolant inlet temperature, 250°F; compression ratio, 7.0.

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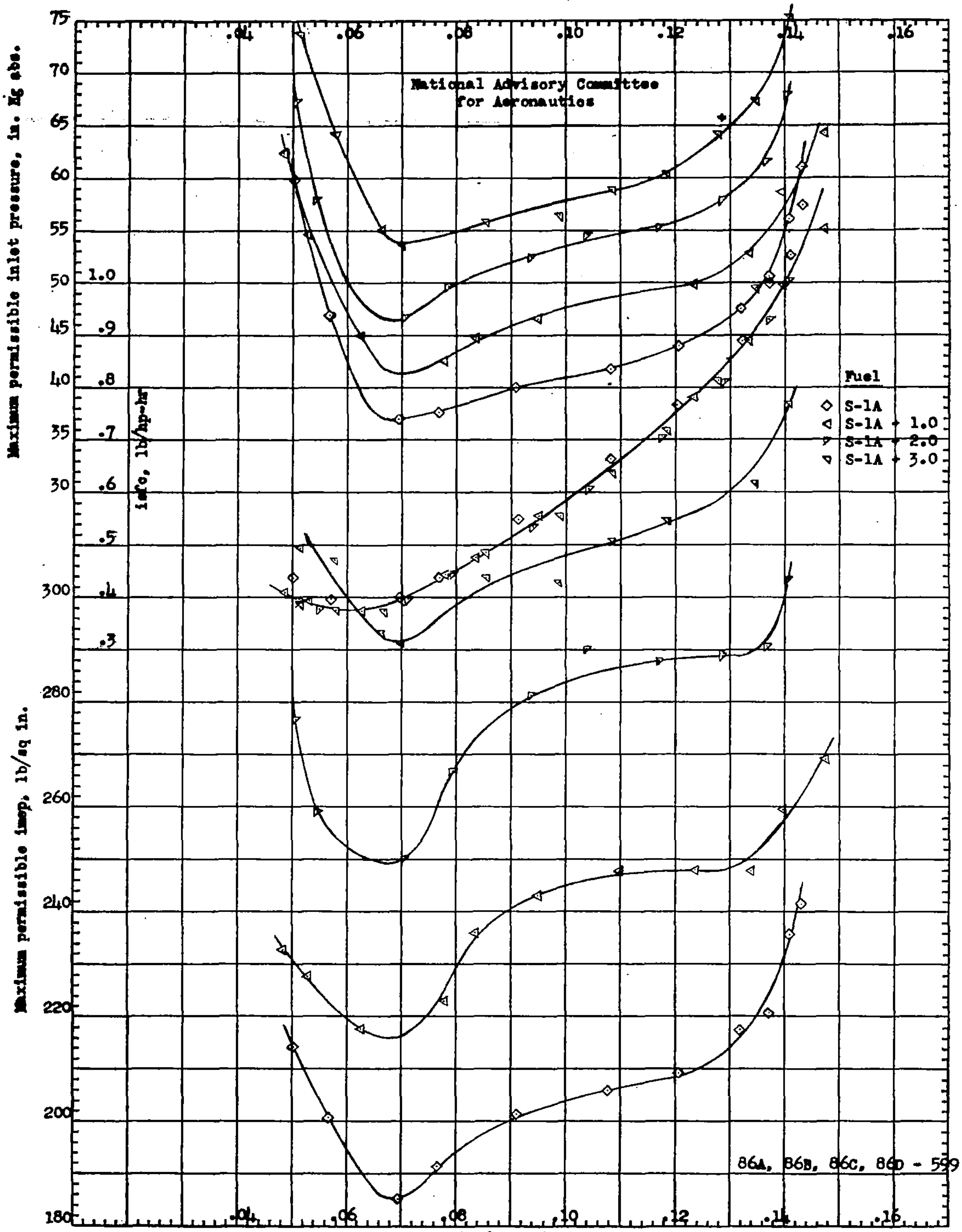


Figure 27. - Performance of reference fuels S-1A and S-1A plus tetraethyl lead at 2000 rpm and 150°F inlet-air temperature. Lycoming O-1230 cylinder; spark advance, 21°; coolant inlet temperature, 250°F; compression ratio, 7.0.

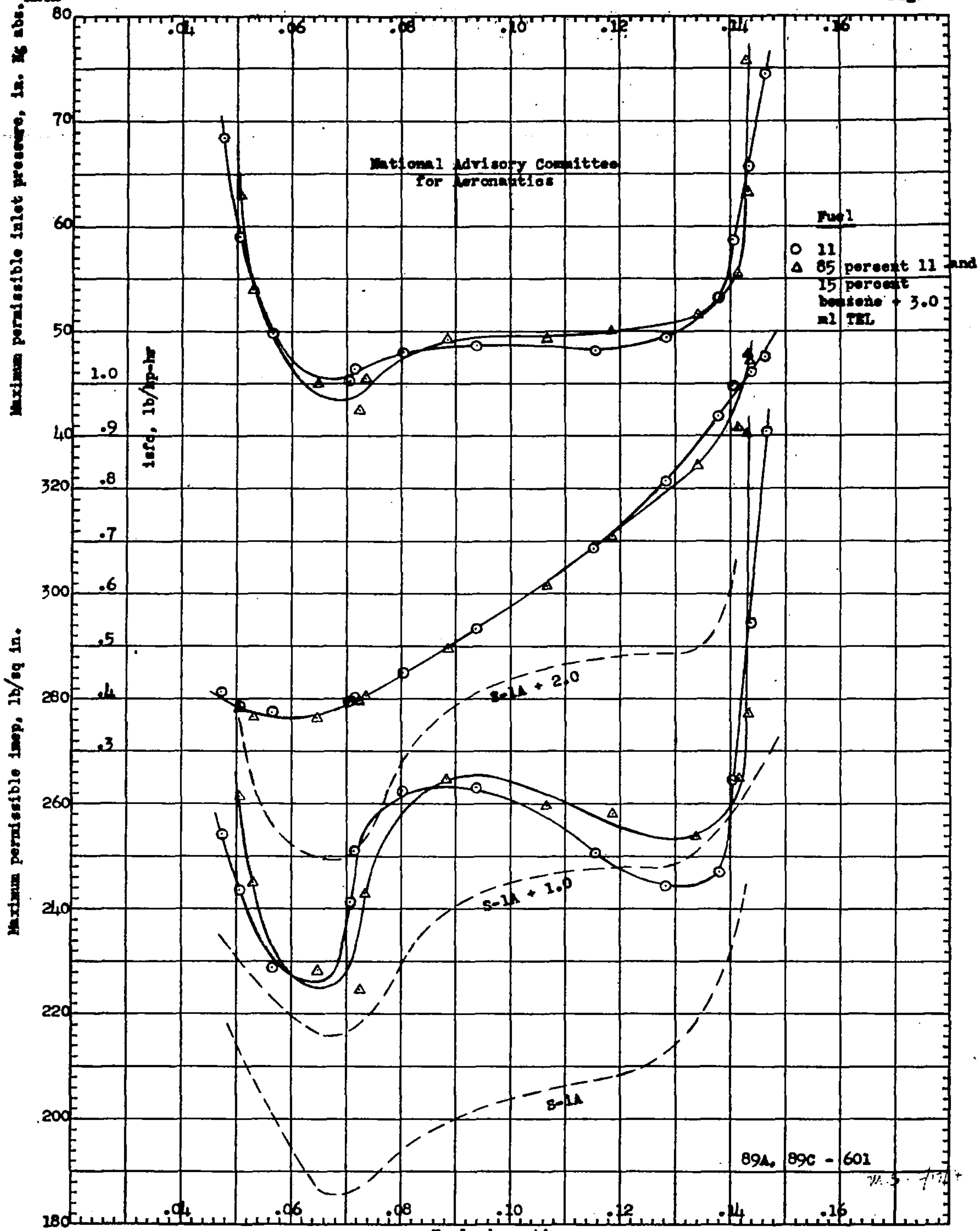


Figure 28. - Performance of NACA fuel 11 with and without addition of leaded benzene at 2000 rpm and 150°F inlet-air temperature. Lycoming O-1230 cylinder; spark advance, 21°; coolant inlet temperature, 150°F; compression ratio, 7.0.

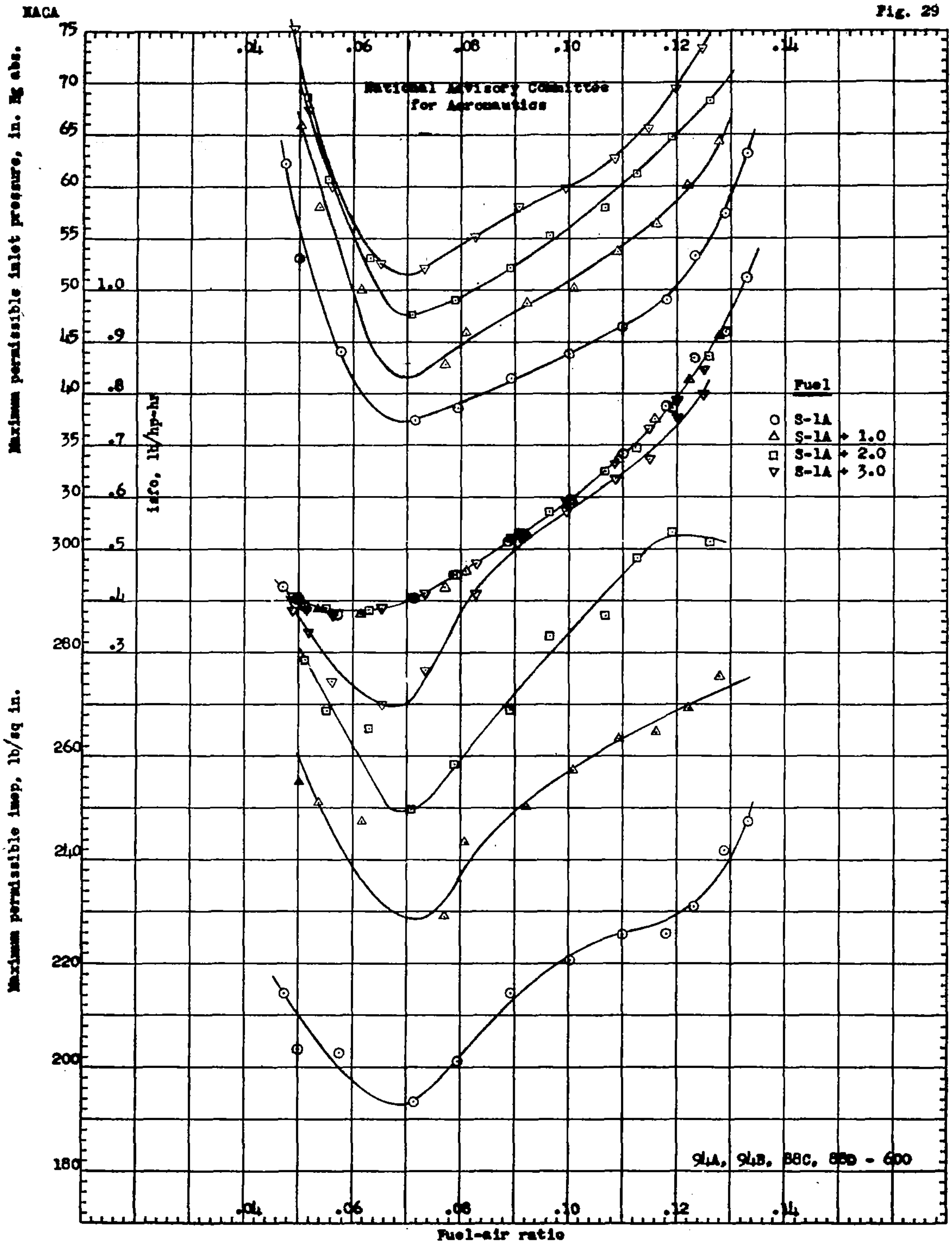


Figure 29. - Performance of reference fuels S-1A and S-1A plus tetraethyl lead at 3100 rpm and 150°F inlet-air temperature. Lycoming 0-1230 cylinder; spark advance, 29°; coolant inlet temperature, 250°F; compression ratio, 7.0.

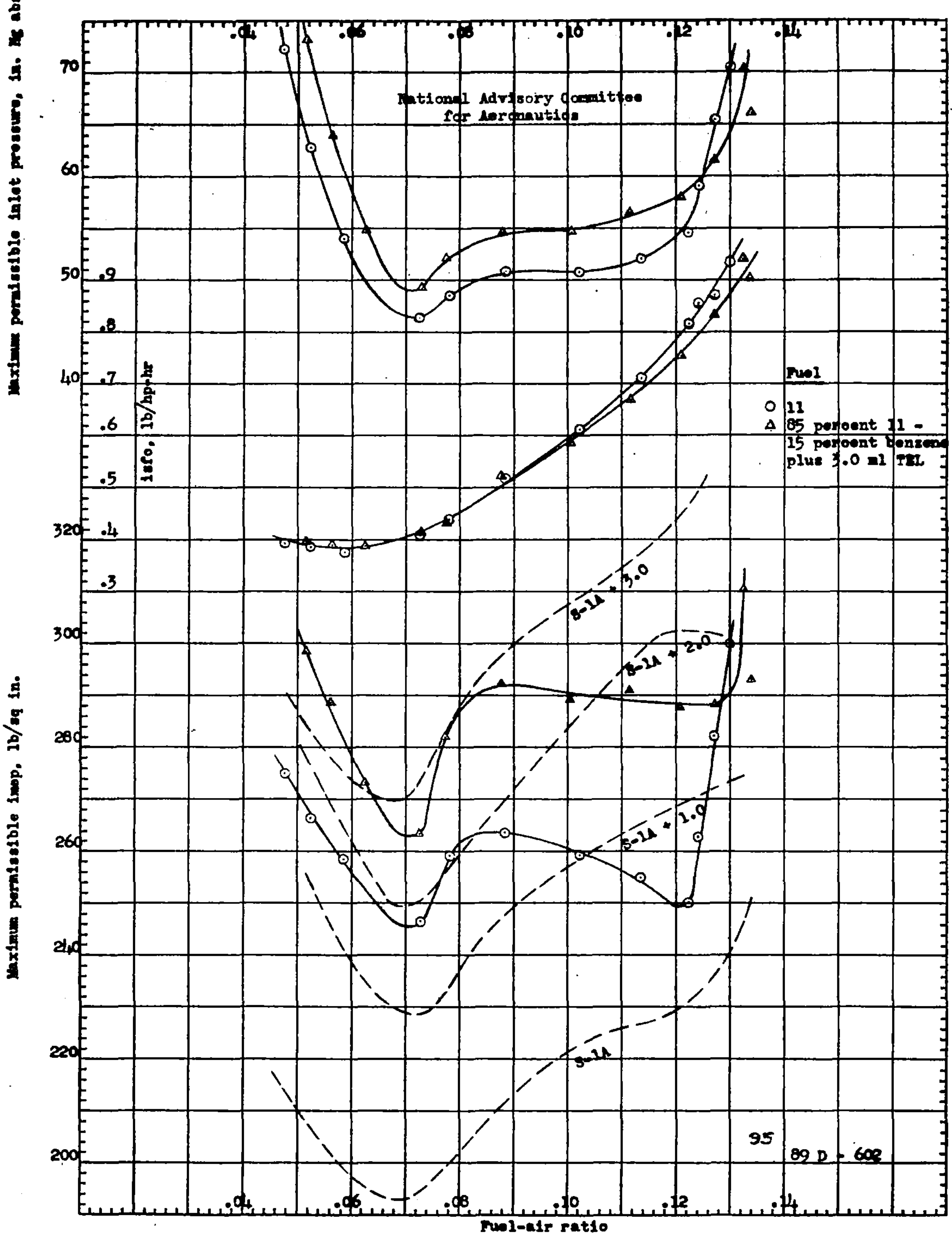


Figure 30. - Performance of NACA fuel 11 with and without addition of leaded benzene at 3100 rpm and 150°F inlet-air temperature. Lycoming O-1230 cylinder; spark advance, 29°; coolant inlet temperature, 250°F; compression ratio, 7.0.

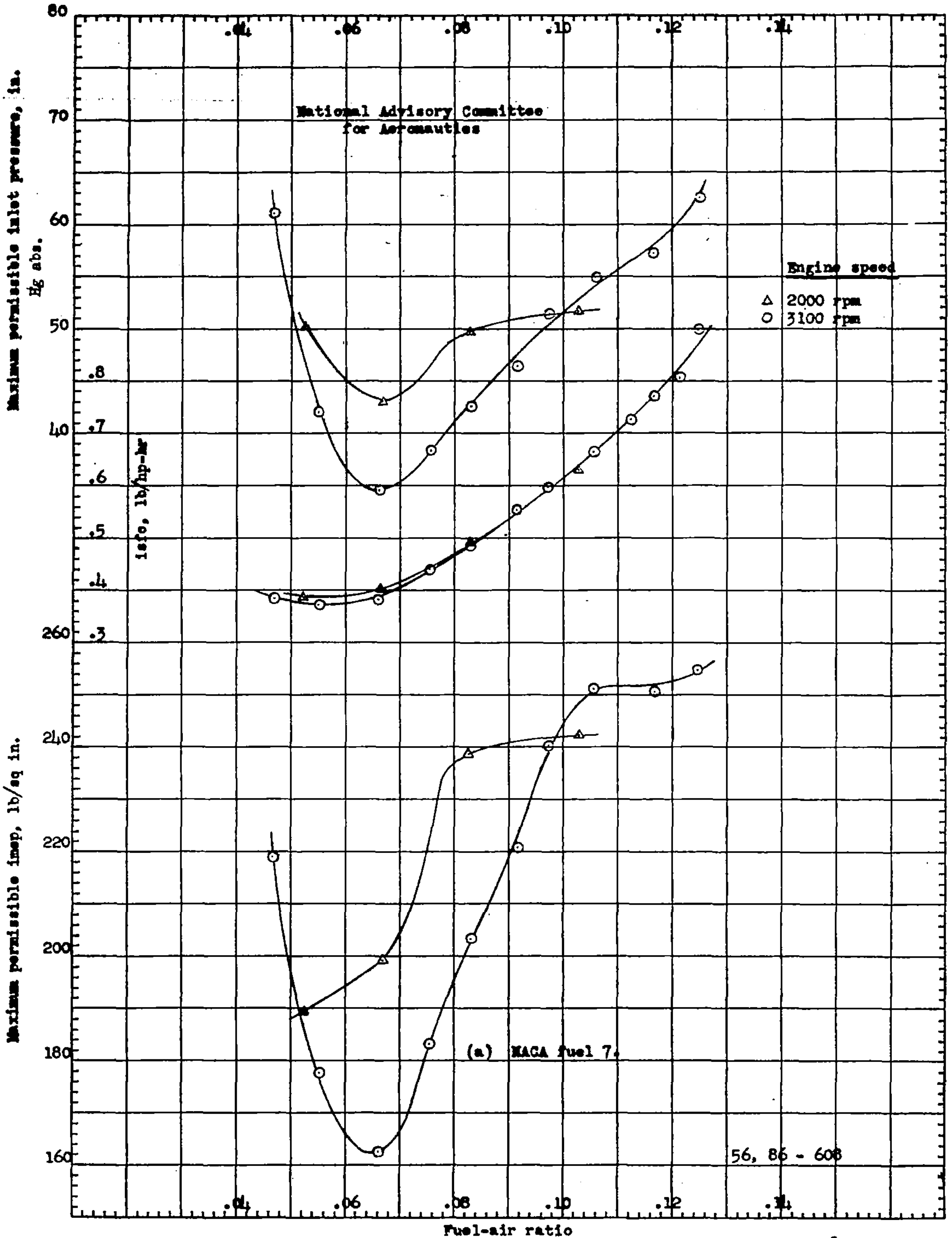


Figure 31. - Effect of engine speed on the performance of NACA fuels 7 to 12 at 250°F inlet-air temperature. Lycoming O-1230 cylinder; spark advance, 29° for 3100 rpm, 21° for 2000 rpm; coolant inlet temperature, 250°F; compression ratio, 7.0.

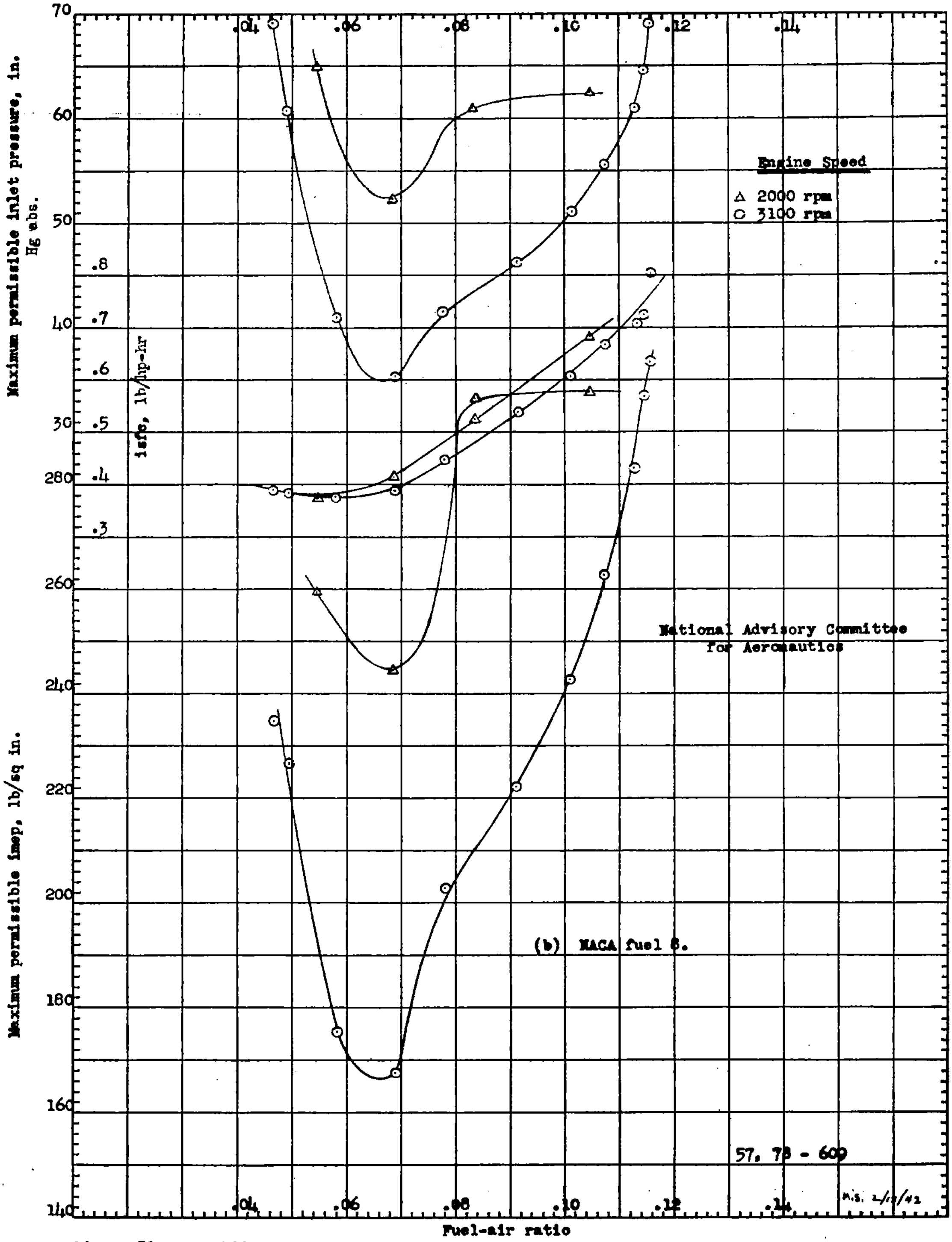


Figure 31. - Cont'd.

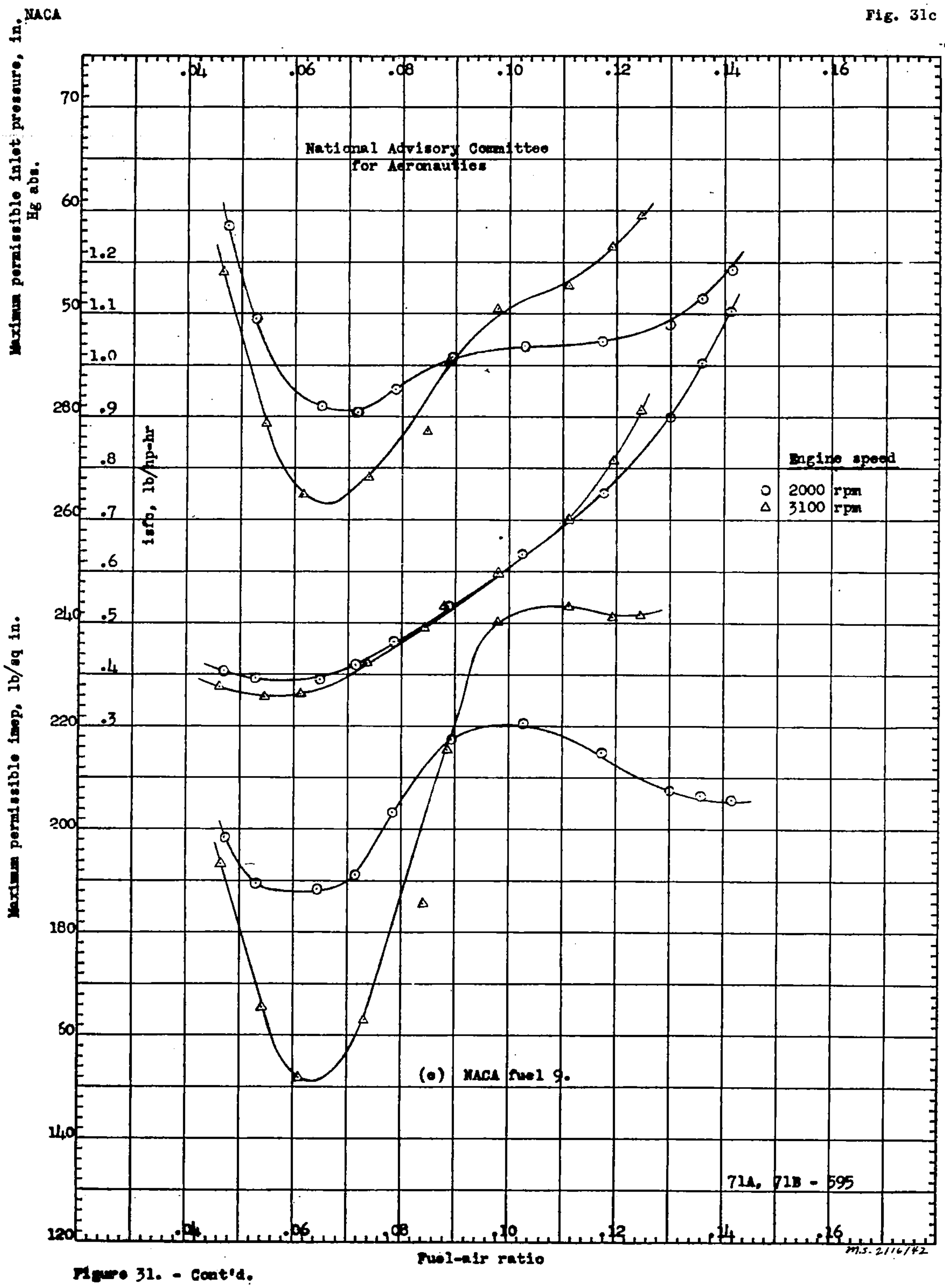
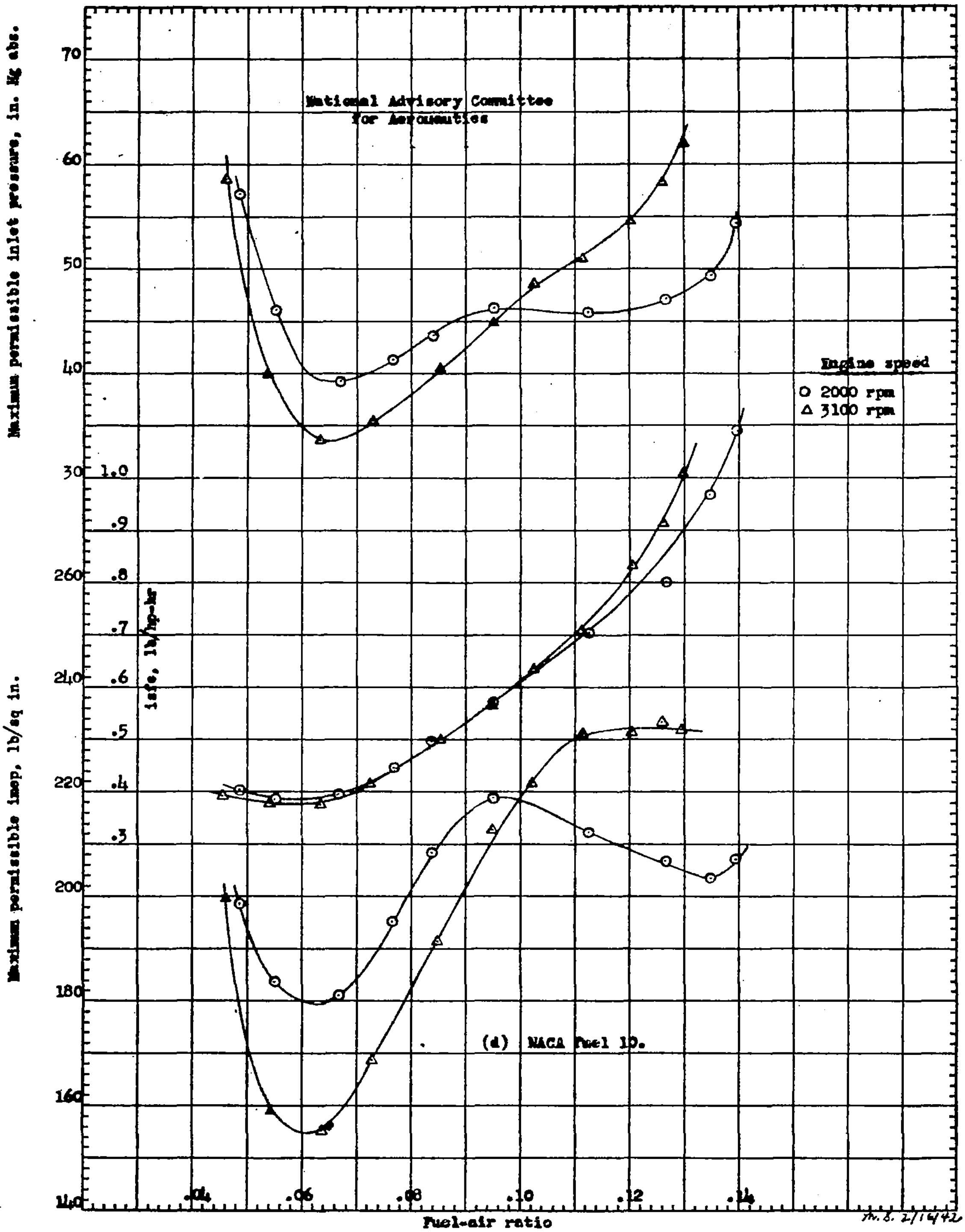


Figure 31. - Cont'd.



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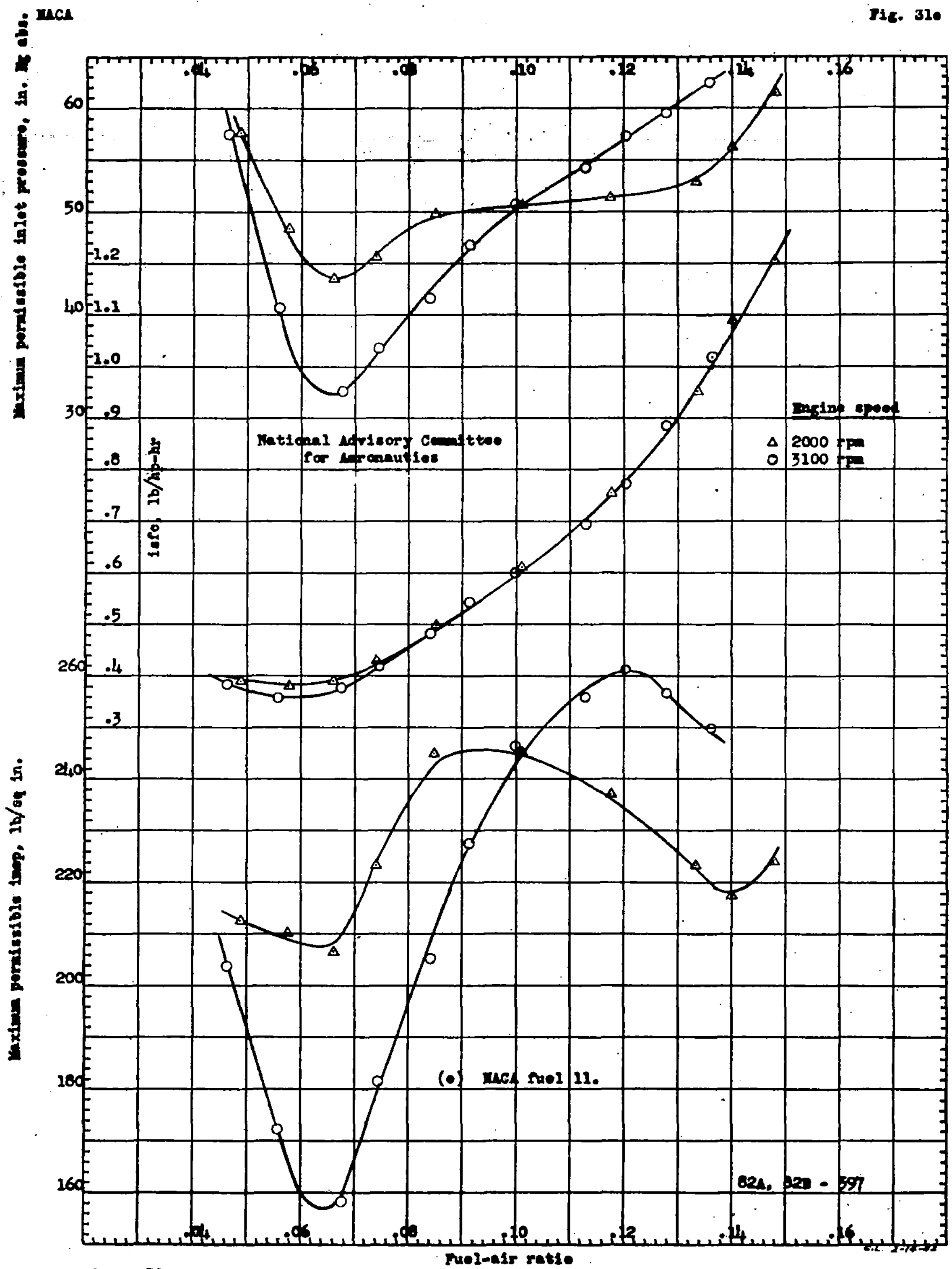

Figure 31. - Cont'd.

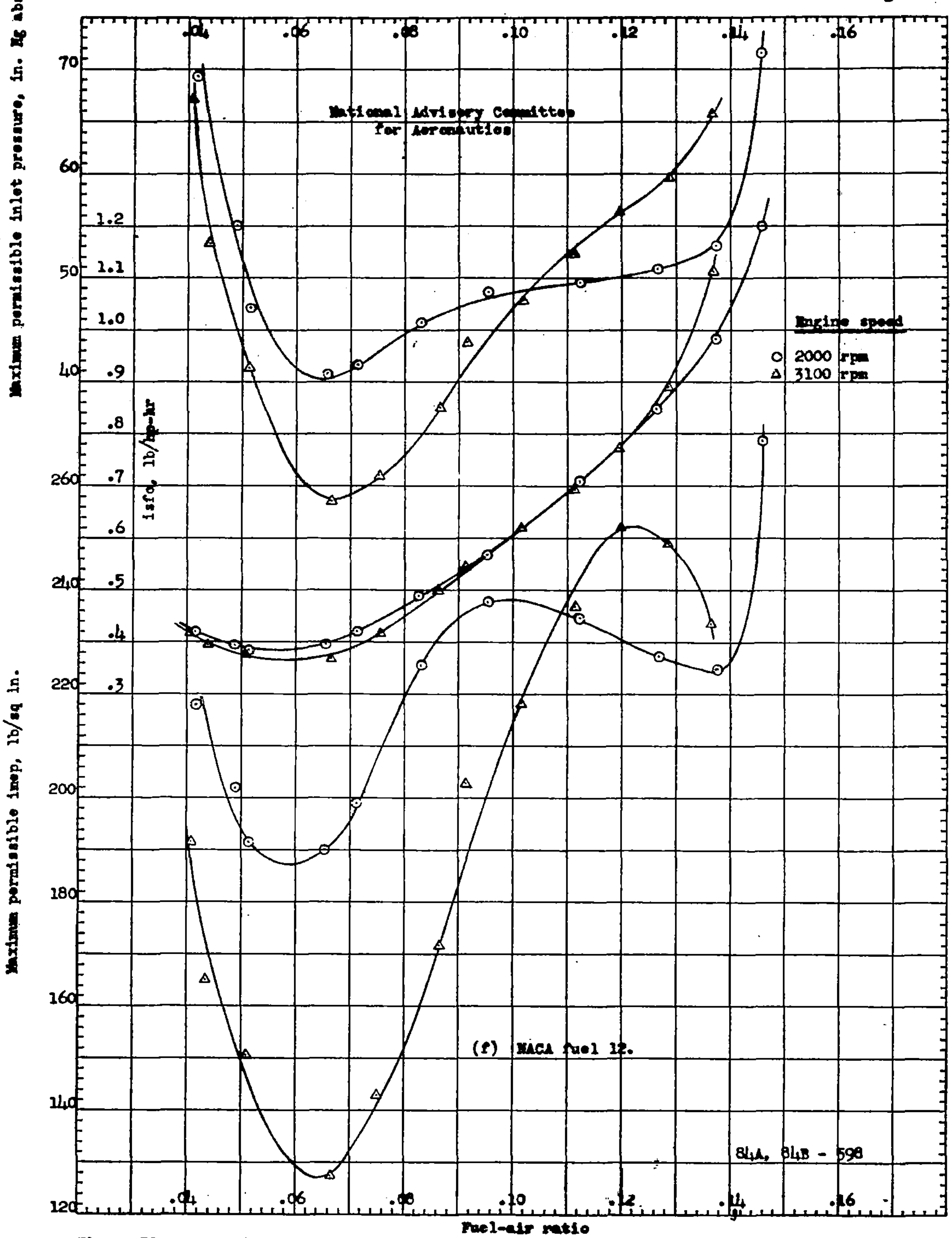

Figure 31. - Cont'd.

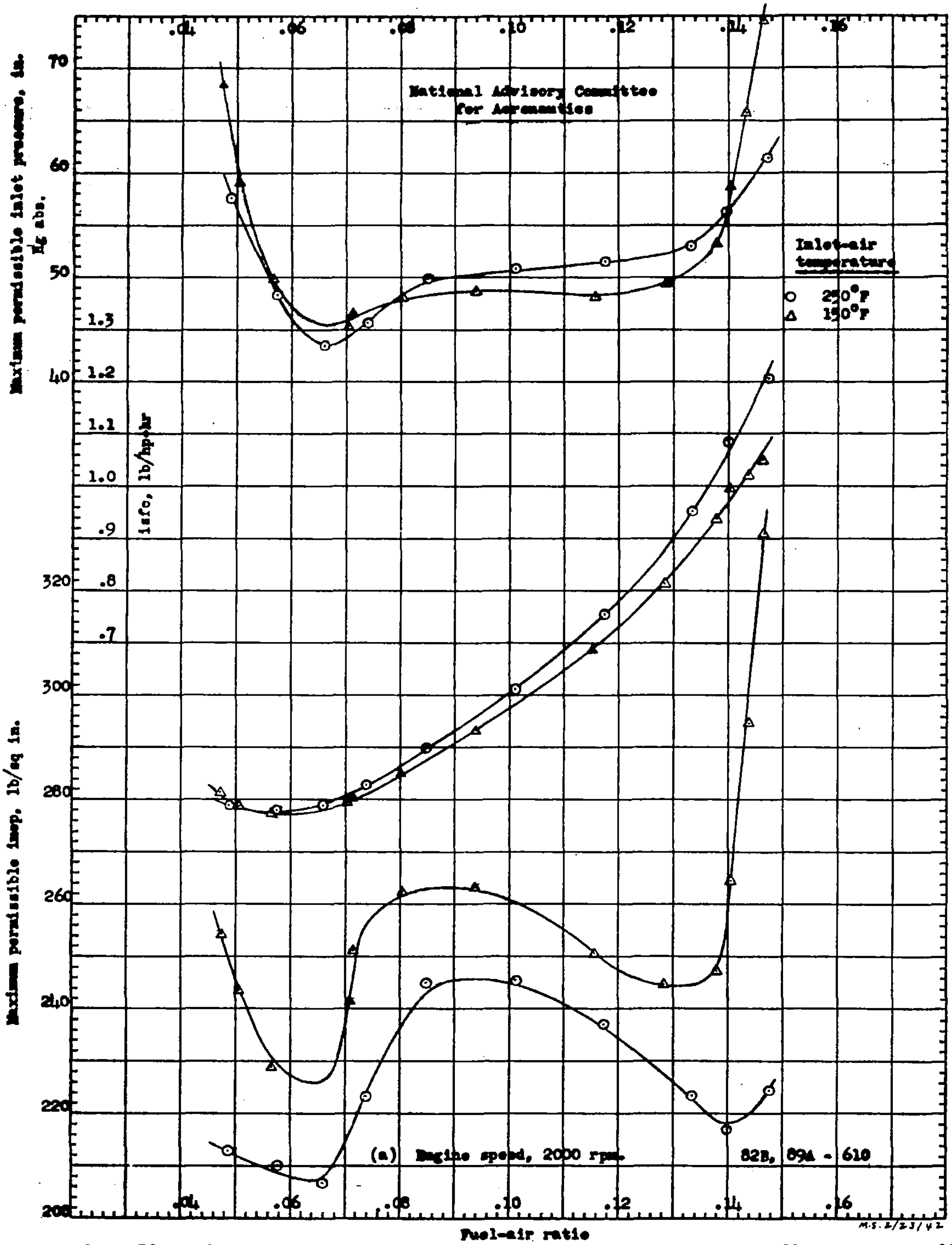

Figure 32. - Effect of inlet-air temperature on the performance of NACA fuel 11. Lycoming O-1230 cylinder; spark advance, 21° for 2000 rpm, 29° for 3100 rpm; coolant inlet temperature, 250°F; compression ratio, 7.0.

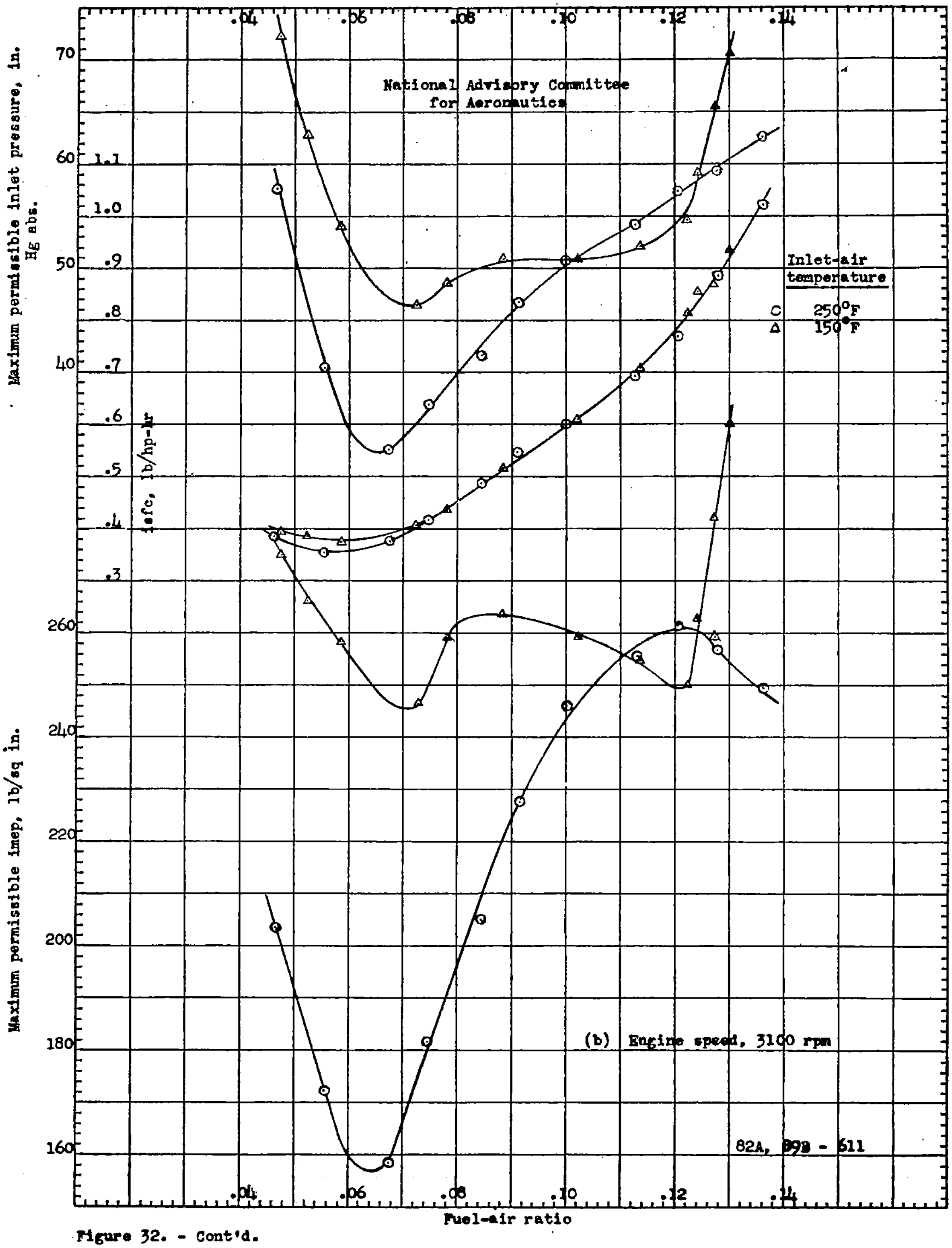

Figure 32. - Cont'd.

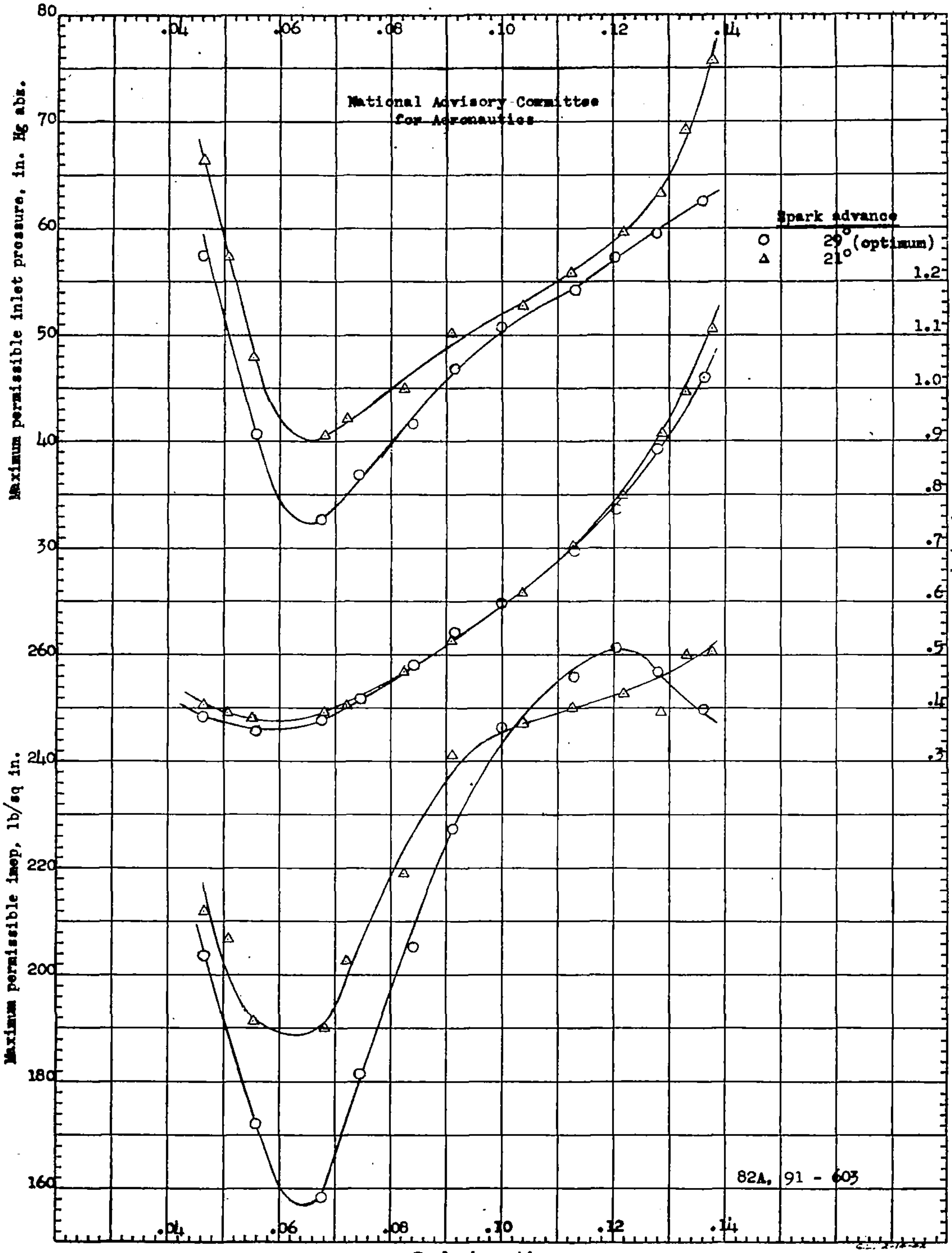

Figure 33. - Effect of retarded spark on performance of NACA fuel 11 at 3100 rpm and 250°F inlet-air temperature. Lycoming O-1230 cylinder; coolant inlet temperature, 250°F; compression ratio, 7.0.